CERTIFICATION OF APPROVAL

The Effect of Various Electrical Potential on CO2 Adsorption and Desorption

By

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Approved by,

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CERTIFICTION OF ORIGINALITY

This is to verify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements and the original work contained herein have not been undertaken or done by unspecified sources or persons.

AHMAD RASYDAN RAMLI

ABSTRACT

An efficient way of removing the amount of CO_2 from the environment is vital to help reduce the greenhouse affecting the world today. In order to do that, several techniques has been developed such as Pressure Swing Adsorption and Temperature Swing Adsorption. This project is conducted based on the Electrical Swing Adsorption technique. The effect of electrical potential applied to the CO2 adsorption and desorption process is observed and studied.

The main objective of the project is to study the effect of various application of electrical potential to the adsorption and desorption process. It is done on a bench scale experiment. Some studies have been done obtain an in-depth knowledge on how the electrical supplied actually affect the adsorption and desorption process. Some recommendations have been made to further improve the experimental setup.

Throughout the studies, the experiment is conducted using any available equipment prepared by the lab in order to have a necessary gas flow loop and a complete electrical circuit within the experimental setup. Some improvement has been done from the previous setup. However it is more towards the safety of the user to avoid electrical shock. The experiment is conducted using 1.5 mm Granular Activated Carbon (GAC). During the adsorption process using CO_2 and desorption process using N_2 and He gas, the gas flow is maintained at approximately 20 kPa. The voltage is varied from 2 – 10 V during adsorption and 0.2 – 1 V during desorption. The result showed that, at an increasing voltage applied the amount adsorbed decreased. Increased voltage reduced the adsorption rate while supporting the desorption rate.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND NOMENCLATURES

ABBREVIATIONS

ESA	Electrical Swing Adsorption
PSA	Pressure Swing Adsorption
TSA	Temperature Swing Adsorption
CFCMS	Carbon Fiber Composite Molecular Sieve
GAC	Granular Activated Carbon
DC	Direct Current
PVC	Polyvinyl Chloride

NOMENCLATURES

CO_2	Carbon Dioxide
kPa	kilo Pascal
atm	Atmosphere (101.325 kPa)
yds	Yards
R	Electrical Resistance (ohm)
V	Volt (J/C)
I	Amperes (C/s)
α	Electric Polarizability
Q	Quadrapole moment
P	Power (J/s)
Q_{ad}	Heat of Adsorption
t	time
s	seconds
C	Coulombs

J	Joules
r	Distance between interacting particles
v	Electronic absorption frequency
E1	Average heat of adsorption of the first layer
E1	Heat of Condensation
D	Distance between atoms per unit volume of each body
C_{pot}	Coefficient in the atom-atom pair potential
ε_0	Absolute permittivity ($\varepsilon_0 = 8.854 \times 10^{-12}\ C_{pot}\ J^{-1}\ m^{-1}$)

CHAPTER 1

INTRODUCTION

1.1 Background of Study

There are several options currently exist to reduce CO_2 emissions. Substituting fossil fuel with non fossil energy source such as nuclear energy has the feature of limiting CO_2 produced. However, they have technical and societal limitations. Currently, the world is focused on capturing CO2 and concentrates it for utilization or disposal. Gas separation is, therefore, a relevant technology in the field of energy production.

A new developing technique of removing CO2 from a mix gas is being developed using Carbon Fiber Composite Material Sieve and a technique called electrical swing adsorption (ESA) recently being developed at Oak Ridge. Using an "electrical swing" separation system, they seem to be inherent advantages over both pressure and temperature swing because separation can be achieved without altering system pressure or applying external heat. However, further development on ESA is essential to have an efficient and reliable process for CO_2 removal. Therefore, this study is to be focused on the effect of applying various electrical potential on CO2 adsorption and desorption.

1.2 Problem Statement

The principle of an Electrical Swing Adsorption (ESA) system is based upon electrical conductivity that is believed to be effective in the separation and capturing of CO_2 at lower cost compare with other separation techniques. Thus, the study of CO_2 adsorption isotherm at various electrical potential is essential to determine the maximum CO_2 uptake.

In the previous study, the application of electrical potential during adsorption has a large difference between each step. During desorption, despite having small potential difference, the electrical potential pattern applied is not consistent. Therefore, there is a need to apply electrical potential for a wide range with small and consistent steps in between the range. This is in order to observe the behavior of the adsorption/desorption process more accurately along the electrical potential applied.

1.3 Objective and Scope of Study

The main objectives of the project are:

1.3.1 To study the adsorption and desorption CO_2 on application various electrical potential using the Electrical Swing Adsorption (ESA) process. The study shall focus on the effect of voltage towards the rate of adsorption, desorption and also the CO_2 uptake.

1.3.2 To compare the effect of different application of voltage towards the effective adsorption and desorption process. This project will focus on covering a more detailed and consistent electrical potential steps over the overall potential range applied

The scope of the study will be only for:

1.3.3 Researching on literature review or previous study regarding the polarizability of the adsorbent and adsorbate towards adsorption and desorption.

1.3.4 Continuing the previous study regarding application of electrical potential towards CO2 adsorption and desorption and further improvement of the ESA project.

The timeframe for the project is only 14 weeks starting from 19th July 2004.

CHAPTER 2

LITERATURE REVIEW AND THEORY

An enhanced gas separation technique is being developed in order to improve the removal of CO2 to help reduce the "green house" gas. This new technology called Electrical Swing Adsorption (ESA) started at Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6088, USA. This laboratory experiment is done using Carbon Fiber Composite Molecular Sieve (CFCMS), an adsorbent developed a variety of gas separation and gas storage applications. Among these applications is the capture of CO_2 from coal fired generation plant exhausts streams.

2.1 Adsorption Process

Adsorption is defined as "a change in concentration of a given substance at the interface with respect to its concentration in the bulk part of the system" [9]. It is connected with the behavior of fluids in a force field extorted by the solid surface. This process depends on many parameters concerning the nature of adsorbate and adsorbent.

Adsorbent-adsorbate interactions in a real situation are always heterogenous. There are many source of heterogeneity (crystal edges and corners, structure of surface etc.). In the case of microporous solids, the main reason is because of the complex geometrical structure containing pores of different sizes and shapes. Therefore a potential field generated by a real solid at a given distance from an adsorbent depends on the position with regard to the surface. Each kind of adsorption site is characterized by its own value of energy of adsorbate-adsorent interactions. Therefore from an adsorption measurement, we can only obtain the "relative heterogeneity" of the adsorbent.

Adsorbents are natural or synthetic materials of amorphous or microcrystalline structure. In the ESA tecnique going to be done, activated carbon is used as the adsorbent to adsorb CO_2 from the bulk fluid. "Activated carbon is a microcrystalline material made by thermal decomposition of wood, vegetable shells, coal and so on, and has surface area of 300 to 1200 m2/g with average pore diameters of 10 to 60 A (angstrom).Activated carbon are classed as hydrophobic (non polar surface)" [10]. Organics are generally adsorbed by activated carbon thus CO_2 can be adsorbed since it is and organic compound.

2.2 Physical Adsorption (physisoprtion)

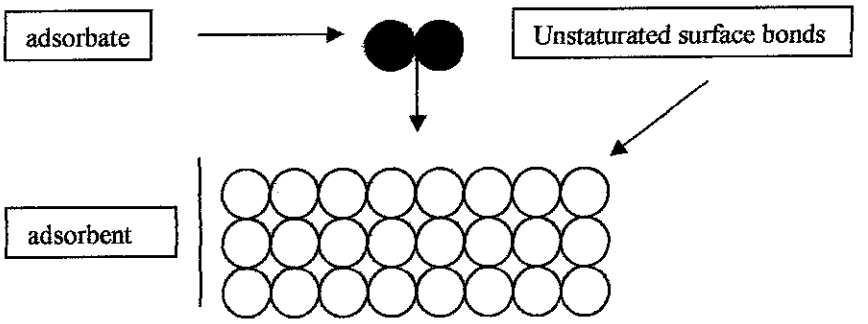
Basically, there are two types of adsorption: the physical and chemical adsorption typically referred as physisorption and chemisorption. Since the interactions between adsorbate-carbon dioxide CO_2 and the adsorbent-activated carbon is mainly physical adsorption, so physisorption will be explained further.

"Physisorption is the relatively weak, nonselective condensation of gaseous molecules on a solid at relatively low temperatures (i.e. – 200 to -25°C); the attractive forces between the adsorbate and adsorbent involve Van der Waals forces, atomic distances typical of a Van der Waals layer and heat of adsorption less than about 15-10 kJ mol^{-1} " [8]. The table below summarizes the characteristic of phsysorption:

Table 2.1: The Description of a Physical Adsorption Process

Parameter	**Description**
Adsorbent	All solids
Adsorbate	All gases below critical temperature
Temperature Range	Low temperature, = bp of adsorbate
Heat of adsorption	Low ($=\Delta H \leq 20$ kJ mol^{-1})
Rate, activation energy	Very rapid, nonactivated
Function of Pressure	Strong
Coverage	Multilayer, nonspecific
Desorption	Easy in vacuum or purge gas
Reversibility	Highly reversible

a) Beginning of the adsorption process



b) Physisorption

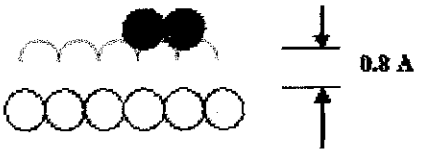


Figure 2.1: The mechanism of physical adsorption process: a) Beginning of adsorption process b) Physisorption

The changes in the volume of gas adsorbed due to physisorption via temperature are shown below:

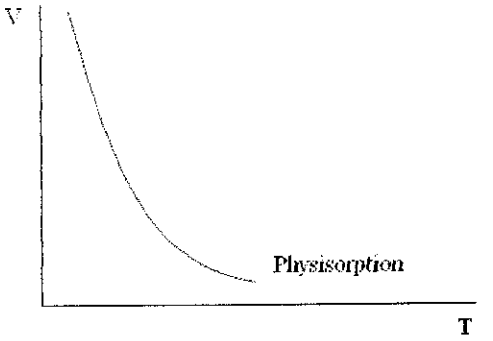


Figure 2.2: Volume of Uptake Changes with respect to Temperature

V = volume of gas adsorbed

T = temperature

The volume of gas physically adsorbed is large at low temperature and decreases sharply with increasing temperature. It drops at higher temperature as the rate of desorption exceeds the rate of adsorption.

2.3 Types of Interactions

There are several types of interaction that occur within an adsorption process.

2.3.1 The Dispersion Interaction

This interaction is also known as London-van der Waals forces, which appear for all material bodies-in particular atoms and molecules due to spontaneous fluctuations in the electromagnetic field (two induced dipole interactions). These fluctuations cause the molecules to posses a non-zero instantaneous dipole moment.

Non polar – non polar interactions:

Figure 2.3: Non polar – non polar molecule interaction

London dispersion energy = $-3h\nu\, \alpha^2 / 4\,(4\pi\, \varepsilon_0)^2\, r^6$

r = distance between the interacting particles

α = the electric polarizibility

v = is the electronic absorption frequency

ε_0 = absolute permittivity, $\varepsilon_0 = 8.854 \times 10^{-12}$ C2 J^{-1} m^{-1}

2.3.2 Interaction between surfaces (big particles)

Three important forces for the long range interaction between macroscopic particles and a surface are steric-polymer forces, electrostatic interactions and Van der waals forces. Assuming that the interactions of two atoms in a vacuum are non-retarded and

additive, the Van der Waals pair potential is : $w = -C/D^6$ where C is the coefficient in the atom-atom pair potential and D is the distance between the tow atoms.

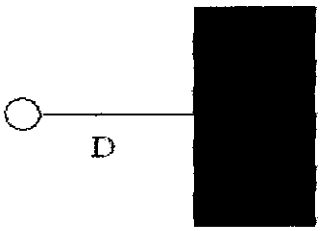


Figure 2.4: Van der Waals interaction free energy, w between an atom and a flat surface

For a non-retarded van der Waals interaction free energy, w between tow atoms.

$\mathbf{W = - \pi C_{pot} P / (6D^3)}$

C_{pot} = coefficient in the atom-atom pair potential

P = the number of atoms per unit volume

D = distance between the atom and the surface

2.4 Adsorption and desorption mechanism

"Activated carbon adsorbs CO2 gas molecules because there is a reduction in the surface energy of the activated carbon when adsorption takes place" [1]. This reduction in energy is adsorption energy and it is exothermic (released as heat when adsorption takes place). Generally, the heat of adsorption increase as the size of the molecule increases. For most activated carbons, adsorption is more efficient with non-polar molecules. Molecules with greater adsorption energy displace molecules of lower adsorption energy.

The adsorption process generally involves 3 mechanisms which affect the process rate. They are:

a) Intraparticle Transport Mechanism
b) Extraparticle Transport and Dispersion Mechanism
c) Heat Transfer

2.4.1 Intraparticle Transport Mechanism

Under this mechanism, several factors can be discussed that limited the intraparticle transport.

1. Pore diffusion in fluid-filled pores. These pores are sufficiently large that the adsorbing molecule escapes the force field of the adsorbent surface. The driving force for such a diffusion process can be approximated by the gradient in mole fraction or if the molar concentration is constant, by the gradient in concentration of the diffusing species within the pores.
2. Solid diffusion in the adsorbed phase. Diffusion in pores is sufficiently small that the diffusing molecule never escapes the force field of the adsorbent surface. In this case, transport may occur by an activated process involving jump between adsorption sites. The driving force for the process can thus be approximated by the gradient in concentration of the species in its adsorbed state.
3. Reaction Kinetics at phase boundaries. Rates of adsorption and desorption in porous adsorbents are generally controlled by mass transfer within the pore network rather than by the kinetics of sorption at the surface.

"In general, bulk flow through the pores of the adsorbent particles is only a small fraction of the total flow; intraparticle convection can affect the transport of very slowly diffusing species such as macromolecules" [9]. The driving force for convection, in this case, is the pressure drop across each particle that is generated by the frictional resistance to flow experienced by the fluid as it flows through the adsorbent.

2.4.2 Extraparticle Transport and Dispersion Mechanism

This mechanisms area affected by the design of the contacting device and depends on the hydronamic conditions outside the particles.

1. External mass Transfer between the external surfaces of the adsorbent particles and the surrounding fluid phase. The driving force is the

concentration difference across the boundary layer that surrounds each particle, and the latter is affected by the hydrodynamic conditions outside the particles.

2. Mixing or lack of mixing, between the different parts of the contacting equipment. This may occur through the existence of a velocity distribution or dead zones in a packed bed or through the inefficient mixing in an agitated contactor.

2.4.3 Heat Transfer

Since adsorption is generally accompanied by the evolution of heat, the rate of heat transfer between the adsorbent particles and the fluid phase may be important. "In addition, heat transfer can occur across the column wall in small diameter beds and is important in energy applications of adsorption. For gas adsorption systems, even with highly porous particles, the controlling heat transfer resistance is generally associated with extraparticle transport, so that the temperature within the particles is essentially uniform" [9].

2.5 Electrical enhanced desorption

Previously, the activated carbon that is already concentrated with CO_2 is regenerated either using the Pressure Swing Adsorption (PSA) or the Thermal Swing Adsorption (TSA). "In TSA, the process of desorption take place at a temperature higher than adsorption. The elevation of temperature is used to shift the adsorption equilibrium and affect regeneration of the adsorbent" [9]. Meanwhile, "PSA technique takes place at a pressure lower than the adsorption. Reduction of pressure is also used to shift the adsorption equilibrium and affect the regeneration process" [9].

Previously, Oak Ridge National Laboratory has developed a Carbon Fiber Composite Molecular Sieve, CFCMS. "A CFCMS has a continuous carbon skeleton which imparts electrical conductivity to the material" [4]. Therefore, they have "utilized the electrical properties of CFCMS to effect a rapid desorption of adsorbed gases" [4]. This technique applied is called electrically enhanced desorption or Electrical Swing Adsorption (ESA). In a comparison done, the effect of applying voltage has managed

to reduce desorption time to less than one-third of that for the HE purge gas alone. Therefore it is found that desorption of adsorbed CO_2 can be rapidly induced by the application of an electrical potential.

"Electrical swing has an advantage over TSA or PSA because the separation can be achieved without altering the system pressure or applying external heat" [4]. "It is inherently low in energy process and faster compared to TSA or PSA" [2]. Evidently, the resistance heating effect is acting directly at the adsorption sites resulting in a rapid desorption of adsorbate. The assumption is that the electrical energy is converted into thermal energy and transferred to the adsorbed CO_2.

2.5.1 Ohmic Heating

Ohmic heating is currently used in the food sterilization industry. The heating technique is different because it applies heating directly within the material itself. It uses the inherent electrical resistance of the material to generate heat and depend highly on the electrical conductivity of the material. Activated carbon has a very high conductivity, has suitable for ohmic heating application.

The heating is simply defined as:

$$\mathbf{P = I^2R = V^2/R}$$

P = power **V** = voltage applied **R** = total series resistance of the system **I** = electrical current

When voltage is applied, the assumption is that the electrical energy is converted to thermal energy and transferred to the gas adsorbate. A relation developed:

Power in heat form = Power in electrical form

$$\frac{\mathbf{Q_{ad}}}{\mathbf{t}} = \frac{\mathbf{V^2}}{\mathbf{R}}$$

$\mathbf{Q_{ad}}$ = heat of adsorption $\mathbf{t}$ = time taken for desorption

From the equation proposed, it can be concluded that the voltage applied is inversely proportional to the time taken for desorption. Therefore as higher voltage is applied, a lower time will be taken for the desorption process.

CHAPTER 3

METHODOLOGY AND PROJECT WORK

3.1 Literature Review and Information Gathering

All the information regarding the ESA process, adsorbent and adsorbate polarizability characteristics are gathered through researching from journals, text books and thesis from previous studies.

3.2 Laboratory Work

Laboratory work will covers the preparation of activated carbon, preparation of experiment setup for electrical enhanced adsorption process, leak and electrical circuit test, adsorption and desorption experiment using different potential.

3.2.1 Objectives of the Experiment

The objectives of the experiment are derived based on the main objectives of the studies. They are:

a. To obtain data on the application of different voltage towards the adsorption and desorption process (CO_2 uptake and rate of adsorption and desorption)

b. To observe the hysterisis trend of the adsorption and desorption process at the end of the experiment

c. To obtain the trend of rate of adsorption and desorption with respect to voltage application at the end of the experiment

d. To obtain the trend of maximum CO2 uptake with respect to voltage application at the end of the experiment

3.2.2 Experimental Apparatus and Chemicals

The experimental setup is prepared using the equipments, apparatus and chemicals as listed below:

Table 3.1: List of Equipments/glass wares/chemicals/others for experiment purposes

NO	Equipment/ Glassware/ Other	Specifications	Quantity
Electrical Equipments:			
1	Regulated DC Power Supply	Range (0-25V), 3.5A	1
2	Mili Ammeter	Range(0-30mA)	1
3	Voltmeter	Range(0-10V)	1
4	Electrical Wire Connector	75cm	5
5	Copper Wire	1m	2
Other Equipments:			
6	Digital Mini Manometer	Range(0-3000kPa)	1
7	Digital Thermometer	Max 600 deg C	1
8	Digital Balance	Max 3100 deg C	1
9	Vacuum Oven	Max 1000 deg C	1
10	Swagelok Tubing Including T-Junction, 90° bending, etc	6 x 4 mm	1 unit
11	Petri Disc	-	8 unit
12	Spatula	-	1 unit
Chemicals:			
13	Purified N_2	99.99% purity	1 cylinder
14	Purified CO_2	99.99% purity	1 cylinder
15	Purified He	99.99% purity	1 cylinder
16	Granular Activated carbon	1.5 mm particle size	1 kg

3.2.3 List of Experiments

Table 3.2: List of Experiment Conducted at Differetn Adsorption/Desorption Voltages

Exp. No	Adsorption Voltges (V)	Desorption Voltages (V)	Purging Gas
1	2	1.0	He
2	4	0.2	He
3	6	0.4	N_2
4	8	0.6	N_2
5	10	0.8	N_2

3.2.4 Experimental Procedures

The experimental procedures conducted during the study are documented as follows:

A. Preparation of Activated carbon

1. The activated carbon (particles size 1.5mm) is filled into a container.
2. The container with the activated carbon is heated inside an oven at 100°C for 24 hours.
3. Prior to experimental work, the container is taken and kept in dessicator for usage.

B. Preparation of test setup for ESA technique

1. Experiment setup as shown in APPENDIX Fig. 1 is prepared.
2. The tubing is connected from CO2 and N2 gas cylinder to the digital mini manometer (P1 and P2), digital pressure differential gauge (PD) and the activated carbon cylinder in order to have continous flow of CO_2.

3. The tubing at the end of digital manometer (P2) is left open for venting purposes.
4. The electrical connection is connected from positive terminal of the DC power supply with the copper wire going through the tubing in between the inlet of the activated carbon cylinder and the T-junction of the PD. The electrical connection ends at the activated carbon cylinder.

(Caution: Copper wire is ensured to be in contact with the activated carbon)

5. At the other end of the wire (out of tube that is in between the inlet and T-juction of PD), it is connected to ammeter, voltmeter and back to the negative terminal of the power supply to have a complete electrical circuit.
6. Digital thermometer is placed at the 150 ml cylinder (Appendix) and all connections are tightened.

(Caution: Cylinder wrapped with aluminum foil to avoid condensation of water around it)

C. Determination of Mass of Activated Carbon

1. Prior to experiment, the weight of an empty column (vessel for the adsorption and desorption process) is weighted and recorded.
2. Granular Activated Carbon is filled into the column and then weighted and recorded.

D. Electrical Circuit and Leak Test

1. The 150 ml cylinder column with activated carbon and digital thermometer is put in place.(APPENDIX Fig. 1)
2. Voltmeter and ammeter reading is monitored after power supply is on. The electrical connection is checked if there is no reading obtained.
3. Leakage test is done on tubing connection by putting soap solution over the all the tubing connection and CO_2 gas valve is open at PI = 25 kPa.
4. Bubble formation is observed to check any possible leakage.
5. If there is leakage, the connection is tightened up.

(Caution: Experiment must be done in a well ventilated room to avoid any gas hazards)

E. Pre-experiment preparation: Activated Carbon heating and Purging

1. Continued from step 5 from section D, digital manometer (P1 and P2), digital pressure differential gauge (PD), digital thermometer (T1) and balance are switched on.
2. Balance is set to zero.
3. Power supply is on and set at 5.0 V and ammeter and voltmeter readings monitored.
4. The N_2 gas cylinder valve is opened at PI = 20kPa for about 15-20 minutes to purge the activated carbon.

(Note: Purging is done to get a highly regenerated activated carbon free from CO_2)

F. Adsorption experiment using DC current of 2.0V

1. Continued from previous section, P1, P2, PD, T1 and balance is still in switched-on mode.
2. Balance is set to zero.
3. The power supply is set to 2.0 V.
4. The CO2 gas cylinder valve is opened at PI = 20kPa to let the flow of CO_2 gas through the activated carbon.
5. The P1, P2, PD, TI, Voltmeter, Ammeter and balance reading is recorded at an interval of 2 minutes for 50 minutes.

G. Desorption experiment using DC current of 0.2 V and N_2 gas purge

1. CO_2 gas cylinder is closed and N_2 gas cylinder valve is opened at PI = 20kPa
2. Power supply is set at 0.2 V.
3. The P1, P2, PD, TI, Voltmeter, Ammeter and balance reading is recorded at an interval of 1 minutes for 25 minutes(until balance reading is near constant).

(Note: Experiment D, E and F will be repeated at different application of voltage values. New activated carbon will be used for every experiment)

3.2.5 Data Analysis and Comparison

Using the data obtained from the experiments, graphs of CO2 uptake/ mass of activated carbon vs time are plotted. Other graphs plotted:

- Adsorption maximum uptake vs. voltage
- Adsorption rate vs. voltage graph
- Desorption rate vs. voltage graph
- Hysterisis graph of adsorption and desorption
- Temperature vs. Time graph

All the graphical results obtained are analyzed based on the trends of adsorption and desorption process at different potential application. The results are discussed referring to the Ohmic heating theory that supports the Electrical Enhanced Adsorption (ESA) technique.

3.2.6 Report preparation

The report for the experiment is documented as part of the course requirement. It is also to be reviewed for further study and improvement of the ESA technique application.

3.3 Tools Required

3.3.1 Experimental Apparatus and Chemical

Please refer to the experimental apparatus in Table 3.1

3.3.2 Software

- Microsoft Excel and Words

CHAPTER 4

RESULTS AND DISCUSSION

This chapter reviews the results of the analysis from the data obtained from the experimental work done for the ESA experiment. Further discussion on the results of analysis is done to provide further details regarding the effect of ESA technique to the adsorption and desorption process.

4.1 Experimental data

All necessary data regarding the experiment is recorded and presented as follow:

4.1.1 Initial Data

These data were recorded initially before starting the experiment.

4.1.1.1 Mass of Activated Carbon and the Voltage Application

Table 4.1: Mass of Granular Activated Carbon (GAC) in fixed bed column:

Experiment No.	Mass of GAC (g)	Adsorption Voltage (V)	Desorption Voltage (V)	Type of Purging Gas
1	79.88	2	1.0	He
2	80.4	4	0.2	He
3	78.76	6	0.4	N_2
4	77.26	8	0.6	N_2
5	79.27	10	0.8	N_2

Note: The mass of GAC were recorded after pre-heating prior to each experiment

4.1.1.2 CO_2 Adsorption and Desorption Uptake Data

During the experiment the weight, pressure at inlet (P1) and outlet (P2), fixed bed temperature (T) changes were recorded during the conducted experiment at a time interval of 2 minutes for adsorption process and 1 minute for desorption process. The tabulated data obtained can be reviewed in Appendix 1 section.

4.1.2 Experiment Observation

1. During the conducted experiment the voltmeter and ammeter provide an almost constant reading throughout the experiment. Below are the observed Voltage (V) and Current (I) recorded.

Table 4.2: Observed Electrical Current with Increasing Voltage Application

Exp. No	Adsorption Voltage (V)	Current, I (mA)	Desorption Voltage (V)	Current, I (mA)
1	2	10	1.0	6
2	4	24	0.2	2
3	6	38	0.4	3
4	8	54	0.6	4
5	10	62	0.8	4

2. Despite setting the pressure at approximately 20 kPa throughout the experiment, the inlet Pressure (P1) indicates a fluctuation about ± 3 kPa. The outlet Pressure (P2) also fluctuated at ±1 kPa from its tabulated value. (Refer Appendix 1)
3. The CO_2, N_2 and He gasses used provide a cooling effect towards the adsorbent. Condensation occurred around the column during the adsorption of CO_2. No condensation observed during the desorption process.
4. The weight measurement is observed to be fluctuating. This is because of the sensitivity of the balance to the vibration occurring around it.

4.2 Assumptions and Limitations

Several assumptions were made for the experimental work:

1. The thermal conductivity of the activated carbon is assumed to obey the Ohm's Law for power conversion. For simplicity, it is assumed that all electrical energy is converted to thermal energy and transferred to the adsorbed CO_2. However, this assumption is obviously invalid because the energy may have been lost through the resistance of container.
2. The experiment is conducted at a room condition where the atmospheric pressure was 1 atmosphere (101.3 kPa) and at a temperature of 27°C.
3. For simplicity, the CO_2 gas used during the electrically enhanced adsorption process is 99.9% pure. This is different from real application where the CO2 purity may not reach that high therefore affecting the amount of CO_2 uptake.
4. It is assumed that there is no leakage throughout the experiment so that either CO_2 or purging gas of N_2 and He directly flow through the vessel containing the adsorbent.
5. Different type of purging gas, He and N_2 used during the electrically enhanced desorption process is assumed to not effecting the amount of desorption rate.

There was also some limitation to be highlighted during the studies:

1. There is no specific experimental setup for the ESA technique. The experimental setup prepared in the lab was only enough to fulfill the necessary requirement to obtain the data through electrical enhancement. The setup was actually difference compared to the real setup at Oak Ridge National Laboratory. Therefore the accuracy of the experiment may be affected due to the setup used.
2. Due to time constraint, only several of the experiment is run on more than one time.

4.3 Results and Discussion

All the data has been tabulated and the graphical results are reviewed below and discussed concurrently.

4.3.1 Adsorption CO_2 Uptake at Application of Various Voltages

Prior to adsorption process, the GAC was first purge using either He or N2 gas to remove any trapped gas inside the GAC and to obtain a highly regenerated GAC. Therefore an adsorption optimum uptake can be expected for every experiment done. For the adsorption process, the voltage applied is varied at an interval of 2 V starting from 2 V up to 10 V. The voltage is set a consistent 2 V interval in order to compare the results at every voltage increment. Below are the graphical analyses for the adsorption process conducted using a 1.5 mm GAC:

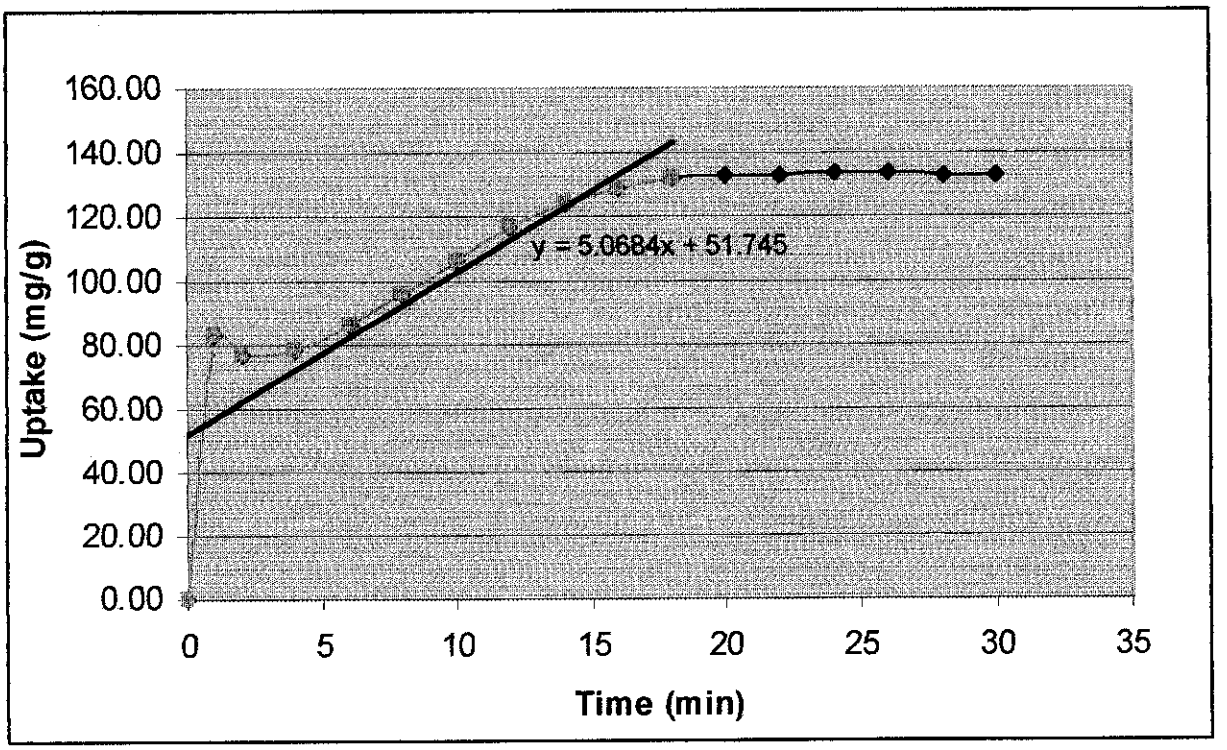


Figure 4.1: Exp 1, Adsorption done at 2V

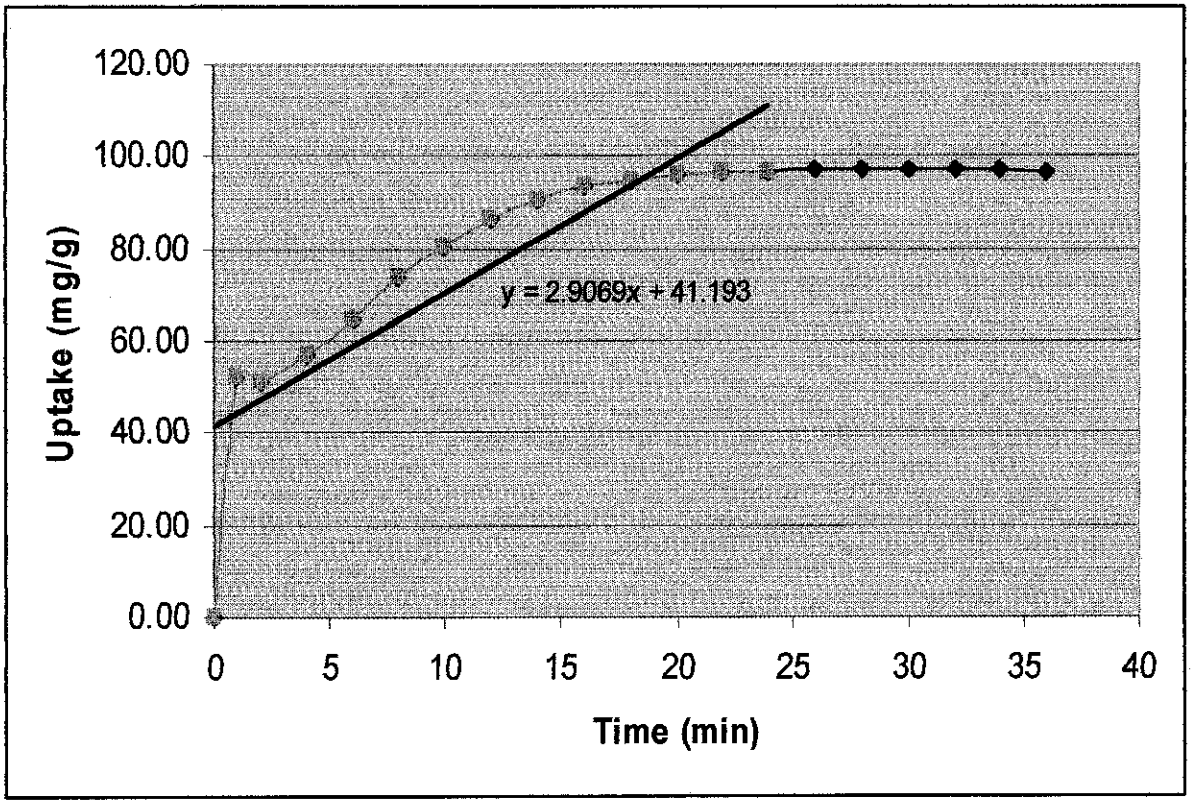


Figure 4.2: Exp 2, Adsorption done at 4 V

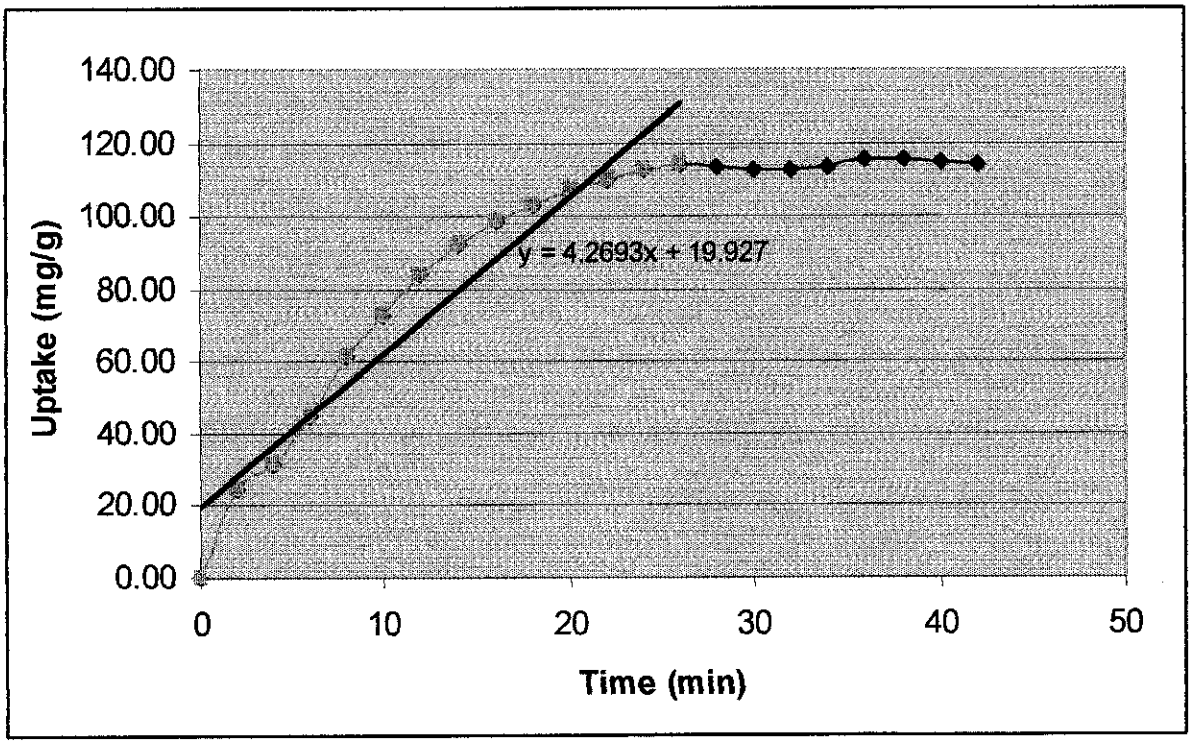


Figure 4.3: Exp 3, Adsorption done at 6 V

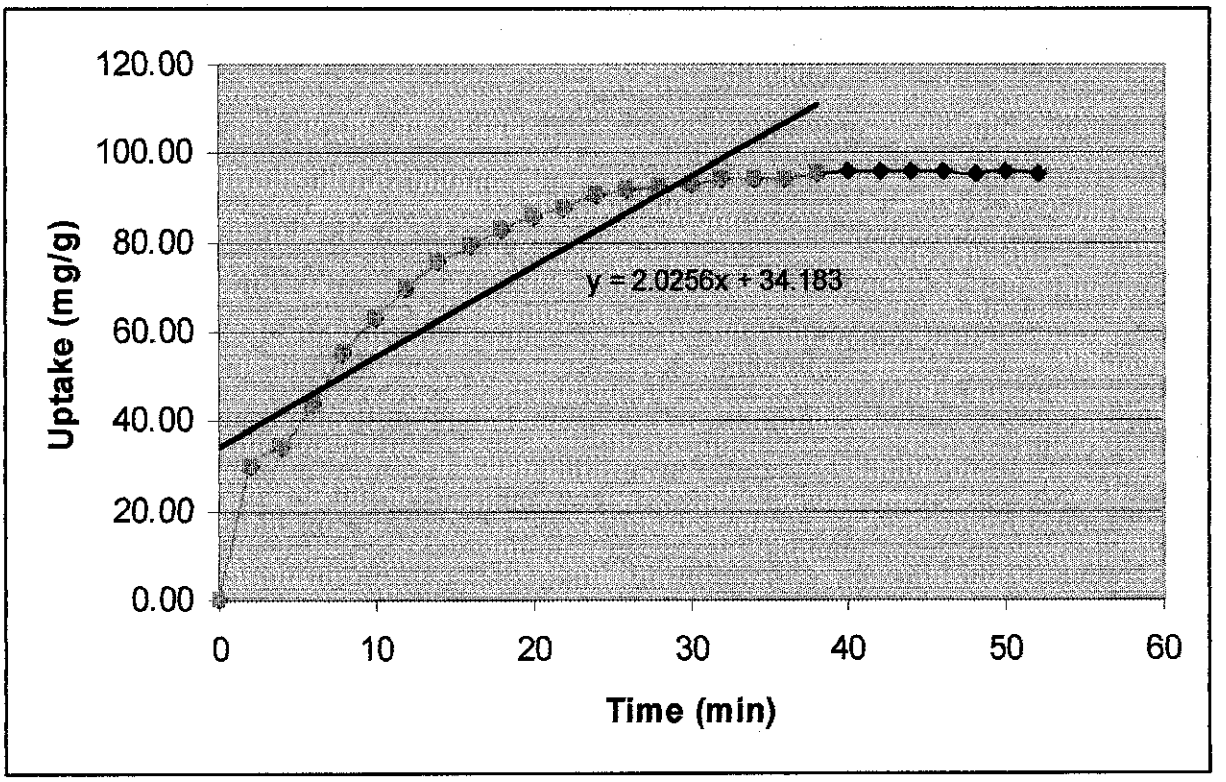


Figure 4.4: Exp 4, Adsorption done at 8 V

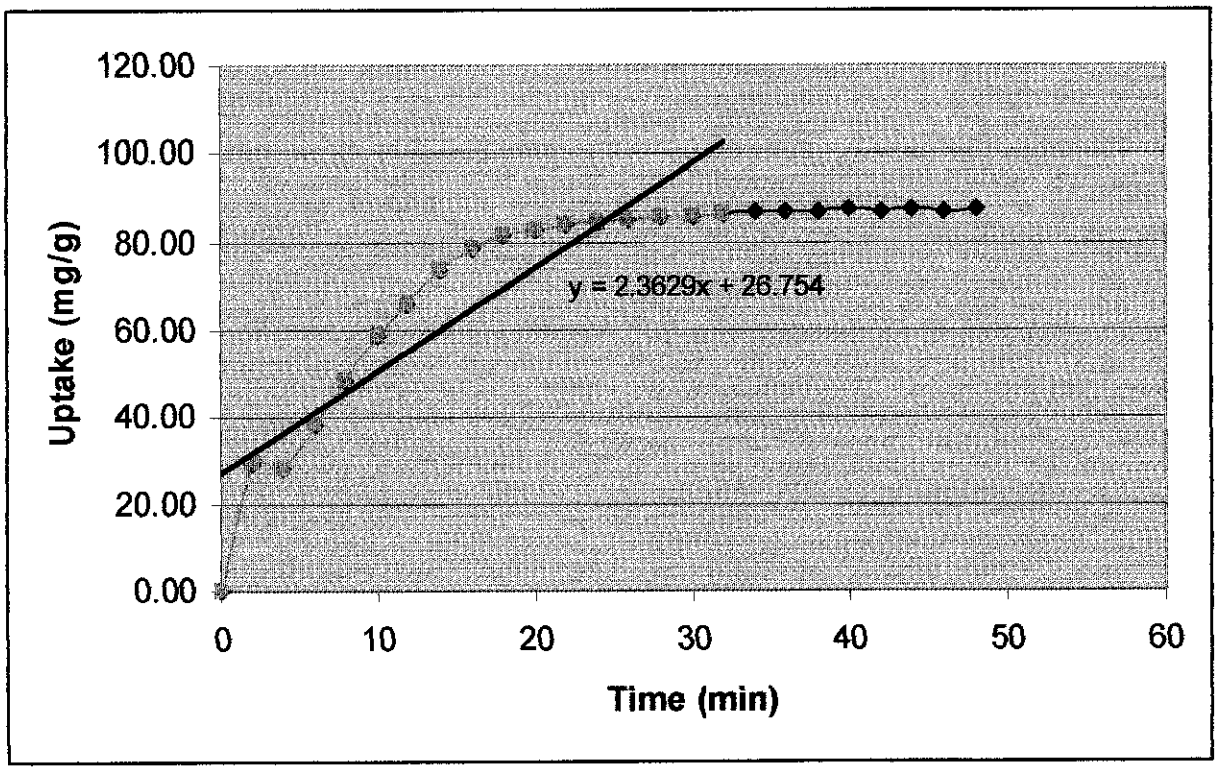


Figure 4.5: Exp 5, Adsorption done at 10 V

The adsorption results from the graph from Fig. 4.1 to Fig. 4.5 have shown that all the adsorption process even at the application of various voltages followed a similar

increasing trend. As shown on the graph, the time taken for the adsorption to reach it maximum uptake is within the range of 25 – 46 minutes. Before reaching its' maximum uptake, the slope of the graph or the local rate of adsorption with respect to time slowly decrease. These observations can be explained by knowing that the fixed bed GAC slowly becoming saturated with CO_2 gas, therefore reducing the rate of adsorption.

After reaching the maximum uptake, the uptake value fluctuates at ± 1% from the maximum uptake. The fluctuation is assumed to be occurring because of the sensitivity of the weight balance equipment. If given a longer time, the amount of maximum uptake may increase, although by small increment. This is because the adsorption process may yet to attain is equilibrium condition. However, the trend results can be accepted due to reaching a stable horizontal uptake after the maximum uptake time.

The table below summarized the results for the maximum uptake, the time taken to reach the maximum uptake and also the rate of adsorption process with respect to the applied voltages.

Table 4.3: The Maximum Uptake and Rate of Adsorption for Different Voltage

Exp. No	Adsorption Voltage (V)	Maximum Uptake (mg/g)	Time to Reach Max. Uptake (min)	Rate of Adsorption ((mg/g)/min)
1	2	133.95	26	5.6084
2	4	97.26	32	2.9069
3	6	115.41	38	4.2693
4	8	96.17	46	2.0256
5	10	87.68	44	2.3629

4.3.2 The Effect Increasing Voltages on Adsorption Process

The effect of application of an increasing voltage towards the adsorption process can be seen clearly in Fig 4.6, 4.7 and 4.8.

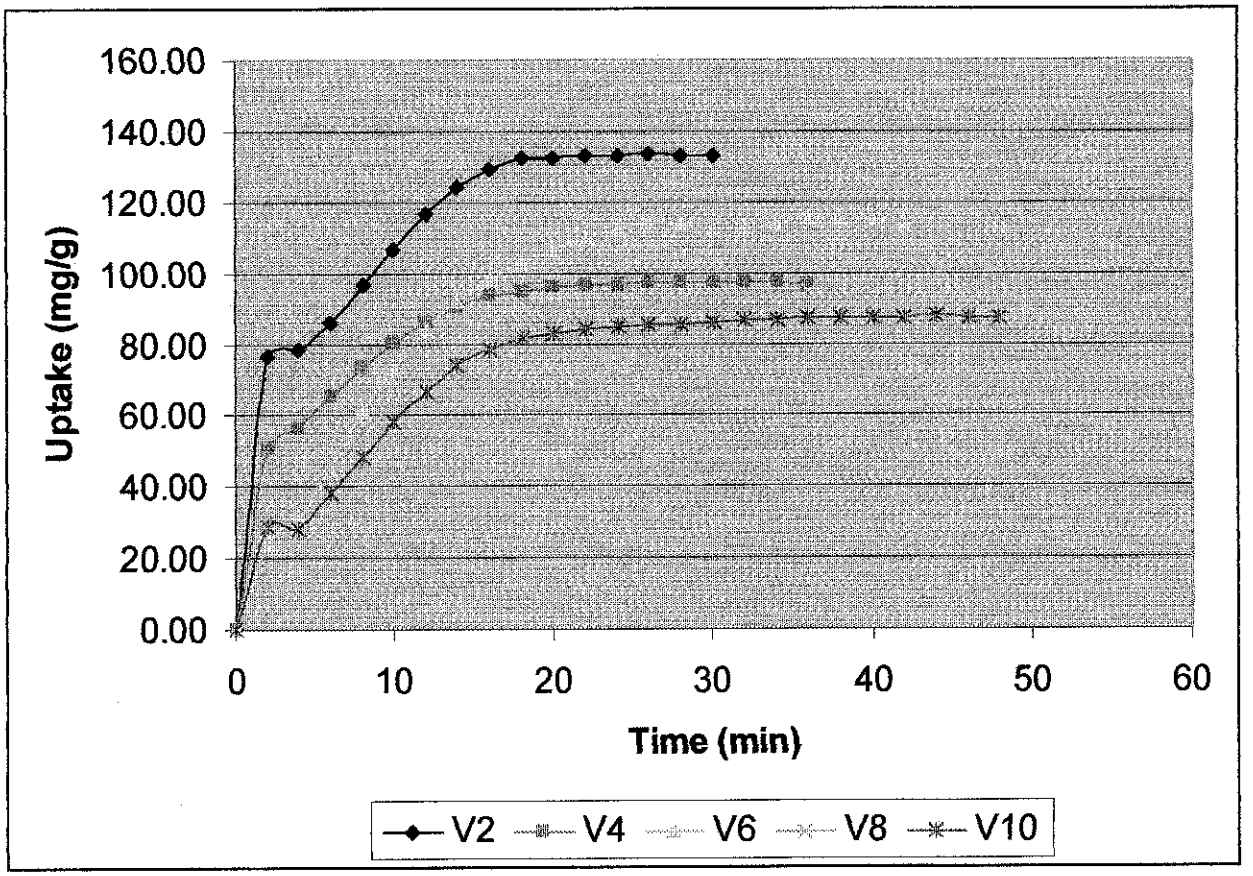


Figure 4.6: The Amount CO2 Uptake at Different Voltages vs Time

As shown and Fig 4.6 and Table 4.1, the time taken for the adsorption process to reach its' maximum uptake increases as the voltage application increases. As explained in the theory, there is a reduction in the surface energy as adsorption takes place. Therefore, when the applied voltages are increased, the amount of energy supplied towards the GAC also increased. This is according to the Ohm's Law:

$$P = I^2R = V^2/R$$

Since adsorption is followed by a reduction in energy, so by adding more energy to the GAC electrically, it opposed the adsorption mechanism, therefore slowing the

adsorption rate and theoretically increasing the desorption rate. The effect is a longer time taken for the adsorption process to reach its equilibrium phase.

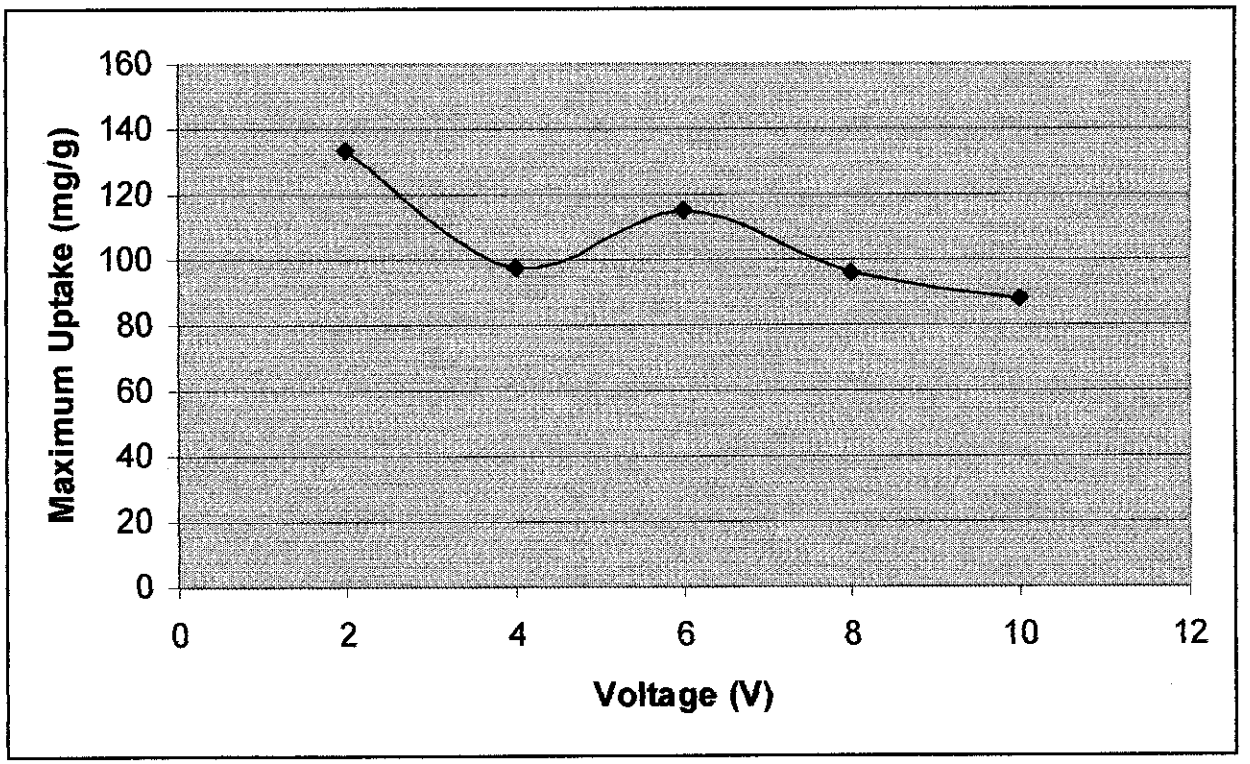


Figure 4.7: Maximum CO_2 Uptake vs. Voltage Applied

The maximum CO_2 uptake is also affected by the increasing application of voltage. Fig. 4.7 and Table 4.1 showed that as voltage increase, the amount of maximum uptake decrease. This can also be explained by the opposing effect of supplying electrical energy towards the GAC. The more energy supplied towards GAC, the more it opposed the adsorption process.

The maximum uptake of GAC is where the equilibrium between adsorption and desorption process is reached since this is a reversible process. At an increased voltage or energy supplied, rate of desorption increase, opposing the rate of adsorption. So, consequently the maximum uptake is reduced due to lower CO_2 adsorption.

However, Fig. 4.7 showed that at application of 6 V, the rate of maximum uptake suddenly increased. This is believed to be an error occurring due to the sensitivity of

the weight balance to the vibration from its' surrounding. The rate is supposed to decrease instead of increasing due to the energy supplementation.

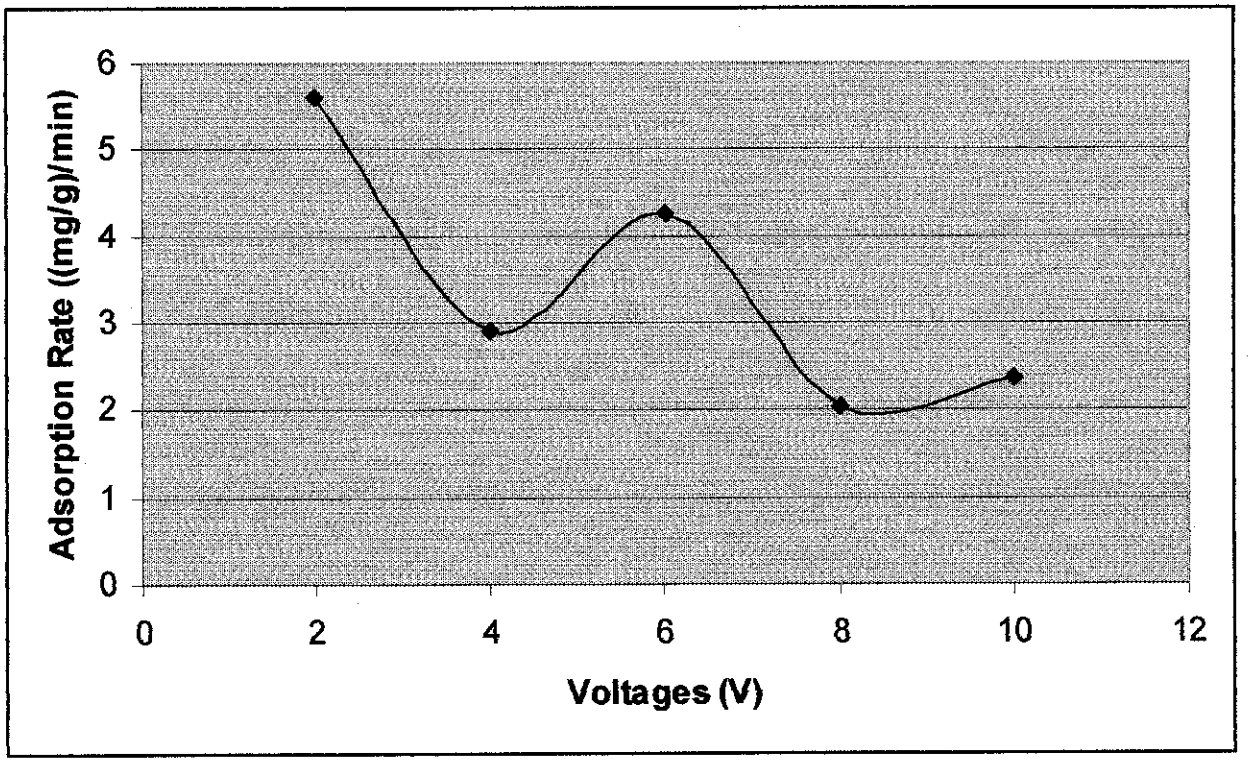


Figure 4.8: Rate of Adsorption vs. Voltage Applied

Fig. 4.8 showed the effect of increasing voltage towards the rate of adsorption. Overall, the rate of adsorption decreased as the application of voltage increased. The adsorption rate recorded is the net adsorption achieved at equilibrium between adsorption and desorption process. Higher voltage increases desorption and opposed the adsorption process. The results are lower adsorption rate achieved at equilibrium.

As explained previously, at 6 V, the rate of adsorption should have been lower. It increased because of equipment problem.

4.3.3 Desorption Results at Application of Various Potential

Desorption process was done after the adsorption process. The desorption or the regeneration process is done at an interval of 0.2 V ranging from 0.2 V to 1.0 V. For experiment 1 and 2, the regeneration process is done using He gas, while for the latter

experiment, purging is done using N_2 gas. Below are the graphical results of the desorption process starting immediately after the desorption process, therefore the value of uptake started to decrease from a higher value.

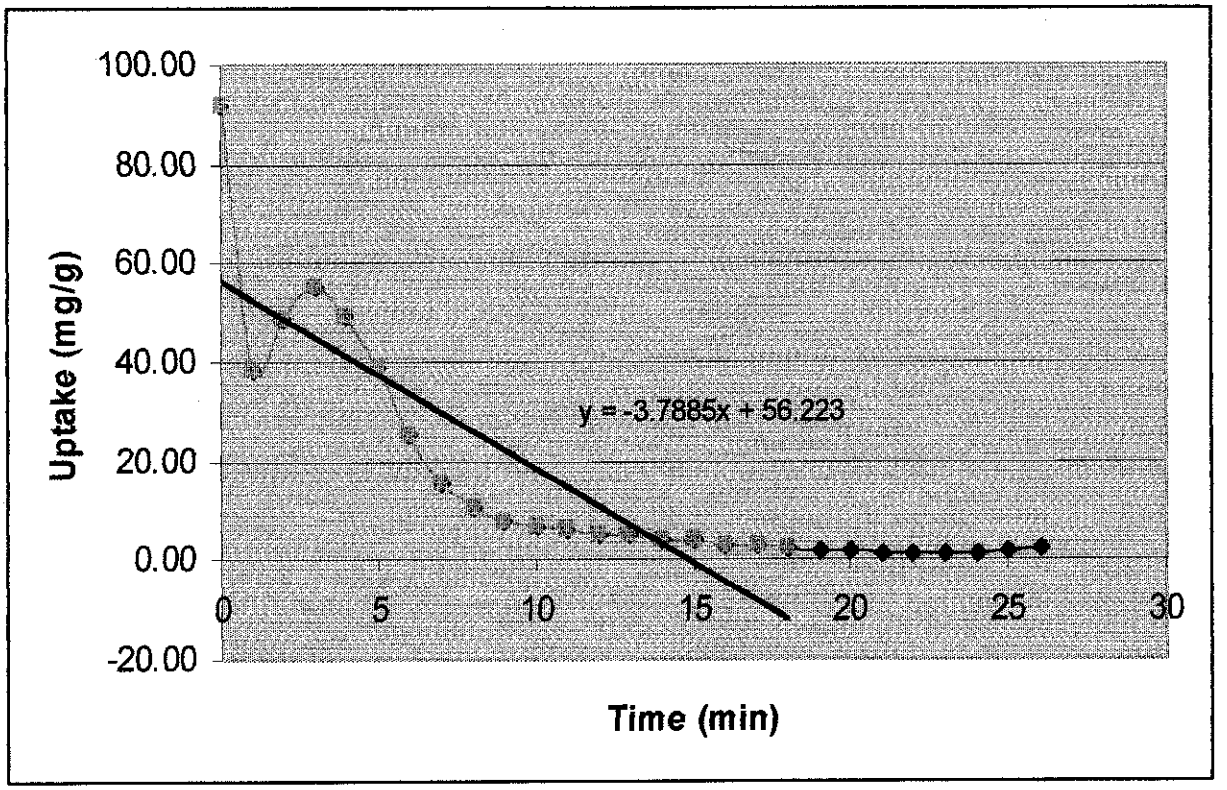


Figure 4.9: Exp 2, Desorption at 0.2 V

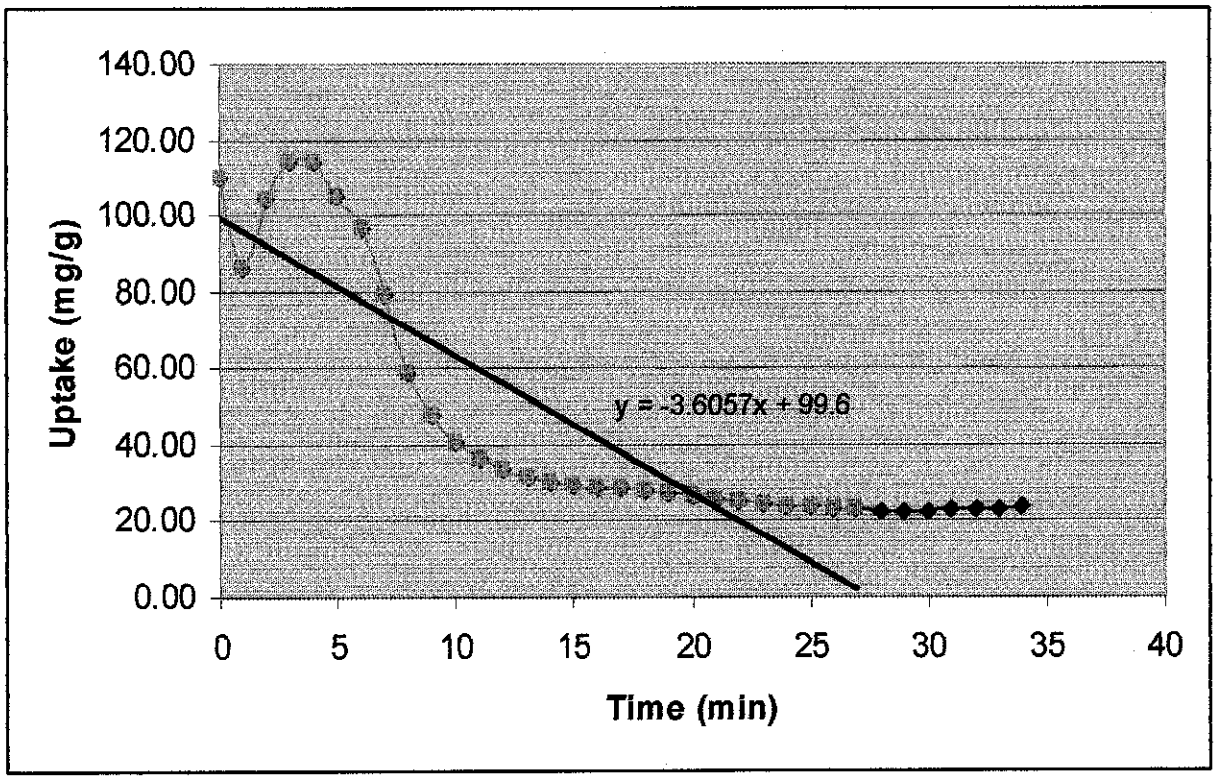


Figure 4.10: Exp 3, Desorption at 0.4 V

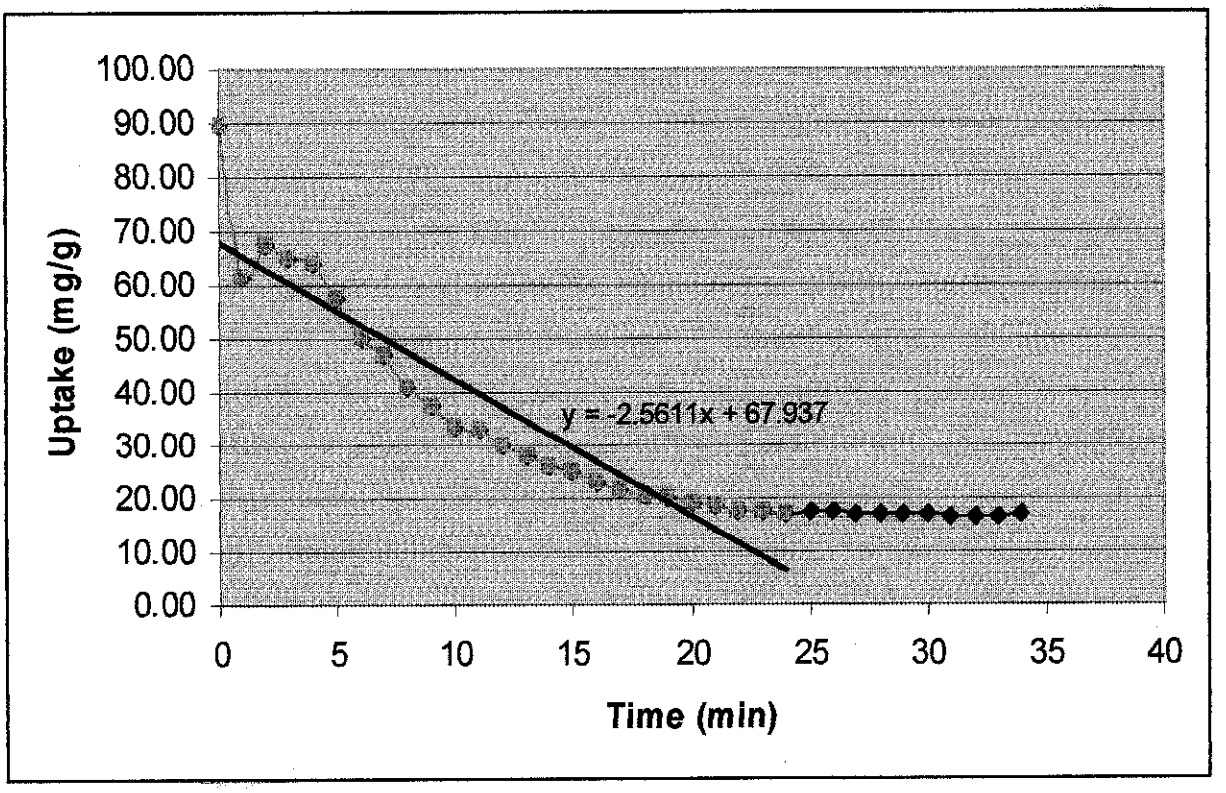


Figure 4.11: Exp 4, Desorption at 0.6 V

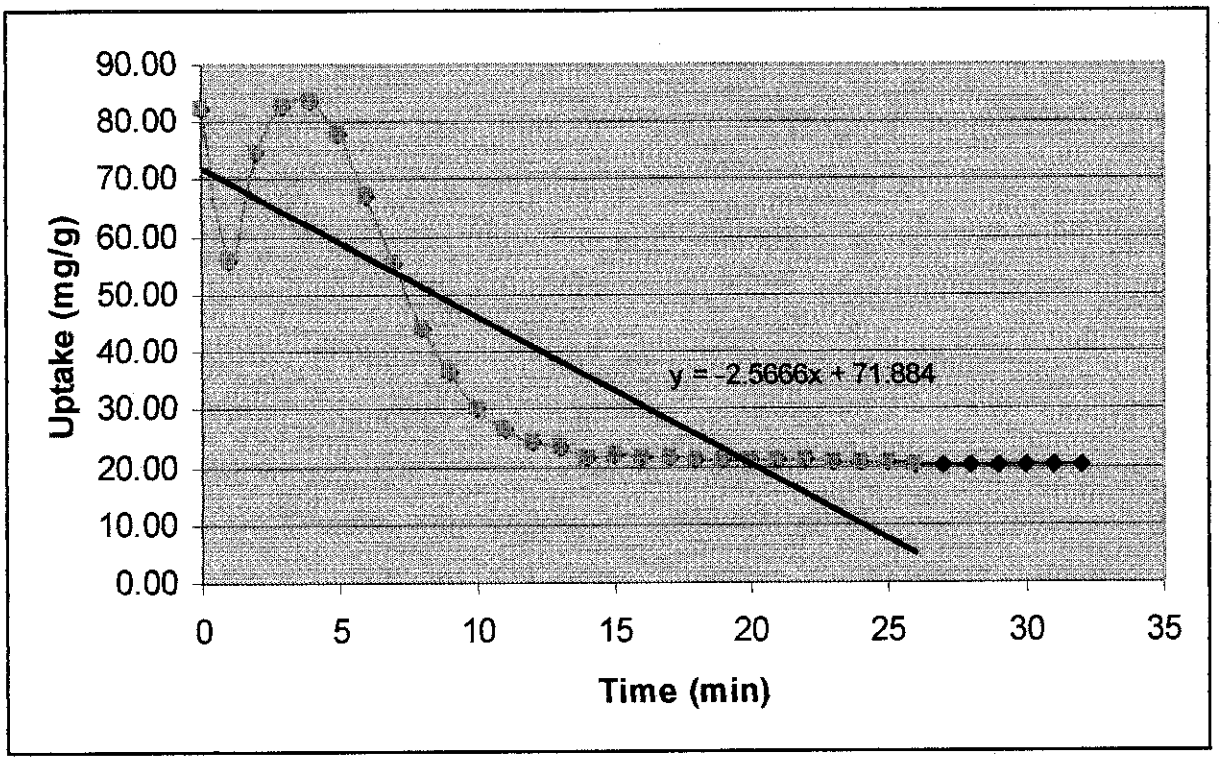


Figure 4.12: Exp 5, Desorption at 0.8 V

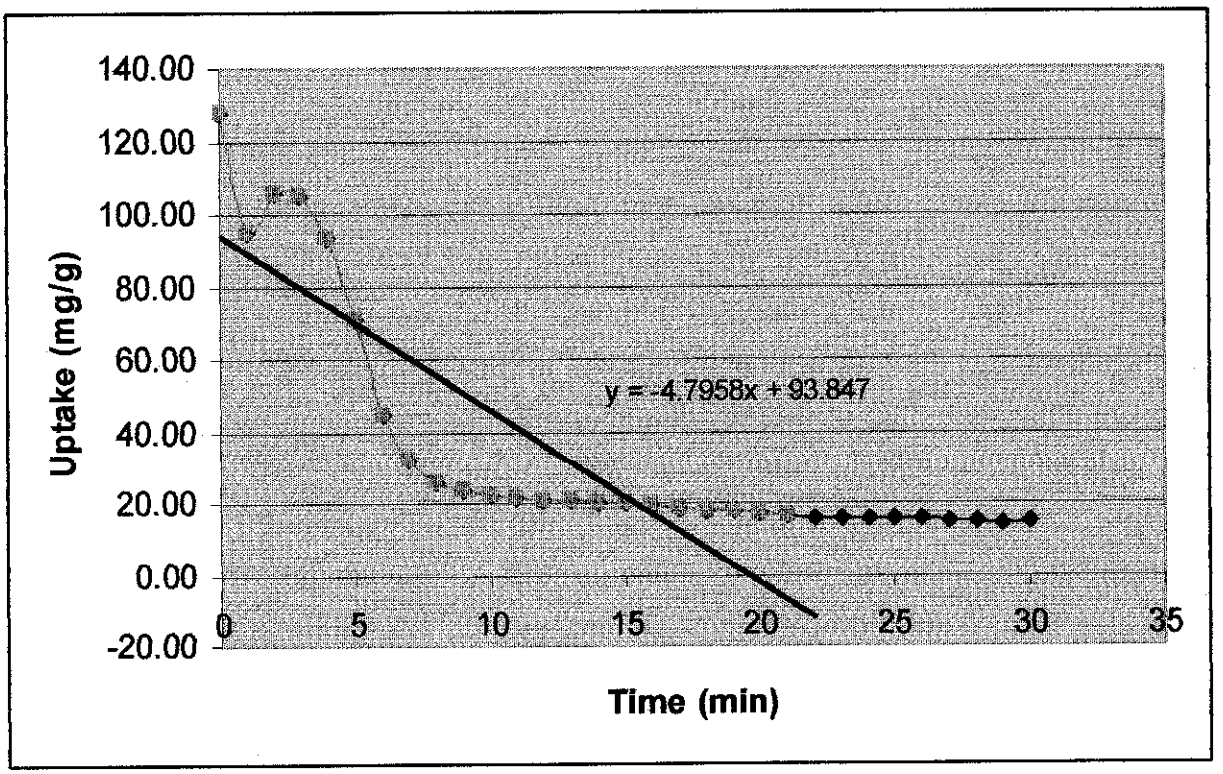


Figure 4.13: Exp 1, Desorption at 1.0 V

Fig. 4.9 up to Fig. 4.13 shows the desorption process. The application of small desorption voltage is because the heat of adsorption for activated carbon is about 30

kJ/mol $^{-1}$. Therefore, only a low amount of electrical energy needed to be applied during the desorption process.The desorption process data is summarized in the table below.

The desorption trend is also the same for each of the desorption experiment at different application of voltage. Immediately after the desorption process started, the amount of CO_2 uptake decreased rapidly within the time range of 0 – 15 minutes. After that, the slope of the desorption rate become more horizontal as the regeneration process is about to reach its effective maximum desorption reduction. After 20 minutes, the weight of the balance become stable indicating the equilibrium achieved for the reduction at their respective voltage application.

The reduction in CO_2 uptake may decrease further if a longer time is taken for each of the experiment. However, from the results obtained, although with additional of energy supplied electrically, the reduction in uptake won't occur until the GAC is fully regenerated. This is because apart from supplying heat to support the desorption process, there are other factors that also influenced the desorption process. There are the intraparticle and extraparticle transport mechanism. During adsorption process, solid diffusion of some of the CO_2 adsorbent may have occurred. Therefore, some of the particle may not desorp due to the force field of the adsorption surface.

Table 4.4: The Uptake Reduction and Rate of Desorption at Different Voltage

Exp. No	Desorption Voltage (V)	Initial Uptake (mg/g)	Uptake Reduction (mg/g)	Percentage of Reduction (%)	Rate of Desorption ((mg/g)/min)
1	0.2	97.26	96.14	98.85	-3.7885
2	0.4	115.41	93.07	80.64	-3.6057
3	0.6	96.17	79.73	82.91	-2.5611
4	0.8	87.68	67.49	76.98	-2.5666
5	1.0	133.95	119.55	89.25	-4.7958

4.3.4 The Effect Increasing Voltages on Desorption Process

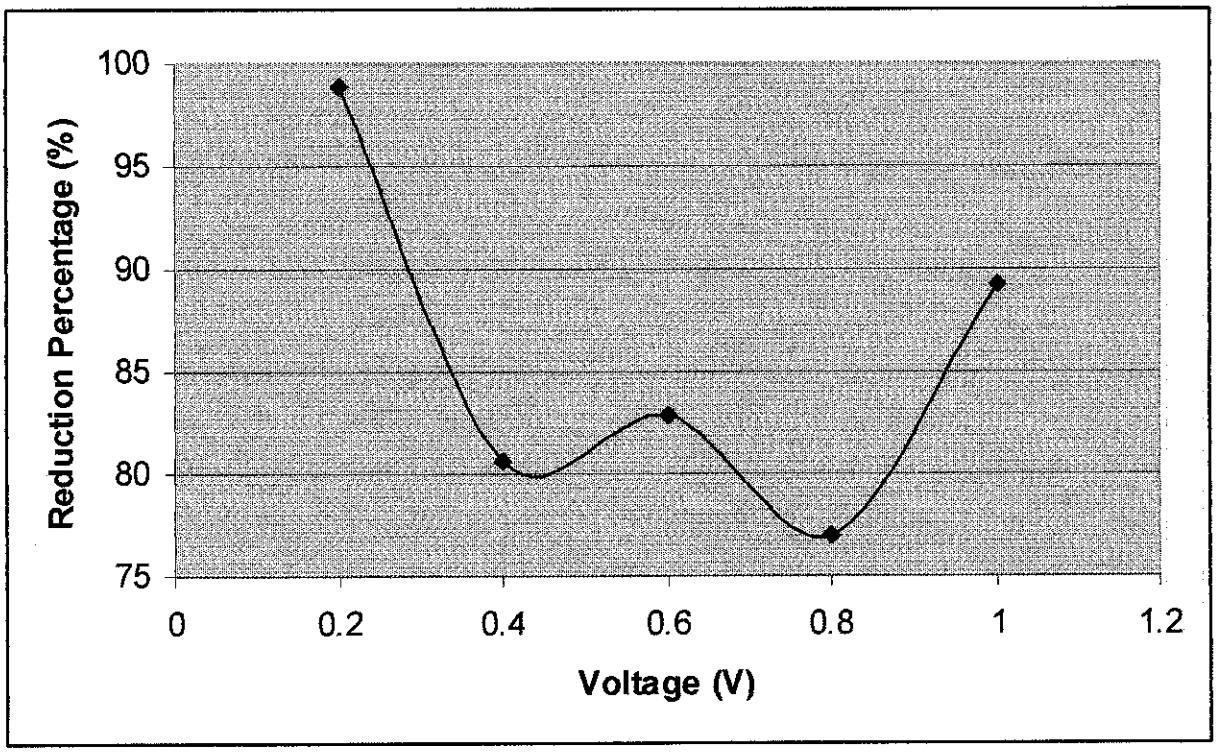


Figure 4.14: The Percentage of Uptake Reduction vs. Voltage

In Fig 4.14 shows the trend of the percentage in CO_2 uptake reduction during the desorption process. At a higher voltage application, the percentages of reduction are expected to increase. Taking at the point where the voltage applications are 0.4, 0.6 and 1.0 V, the increase in the percentage of CO_2 uptake reduction can be seen.

Increasing the voltage will increase the amount of energy supplied according to the Ohm's Law. Therefore, an increasing percentage of reduction is expected. However, it is believed that due to the sensitivity of the weight balance equipment, the expected results is not achieved at 0.2 and 0.8 V application, where the first have the highest reduction and the latter showed a lower reduction.

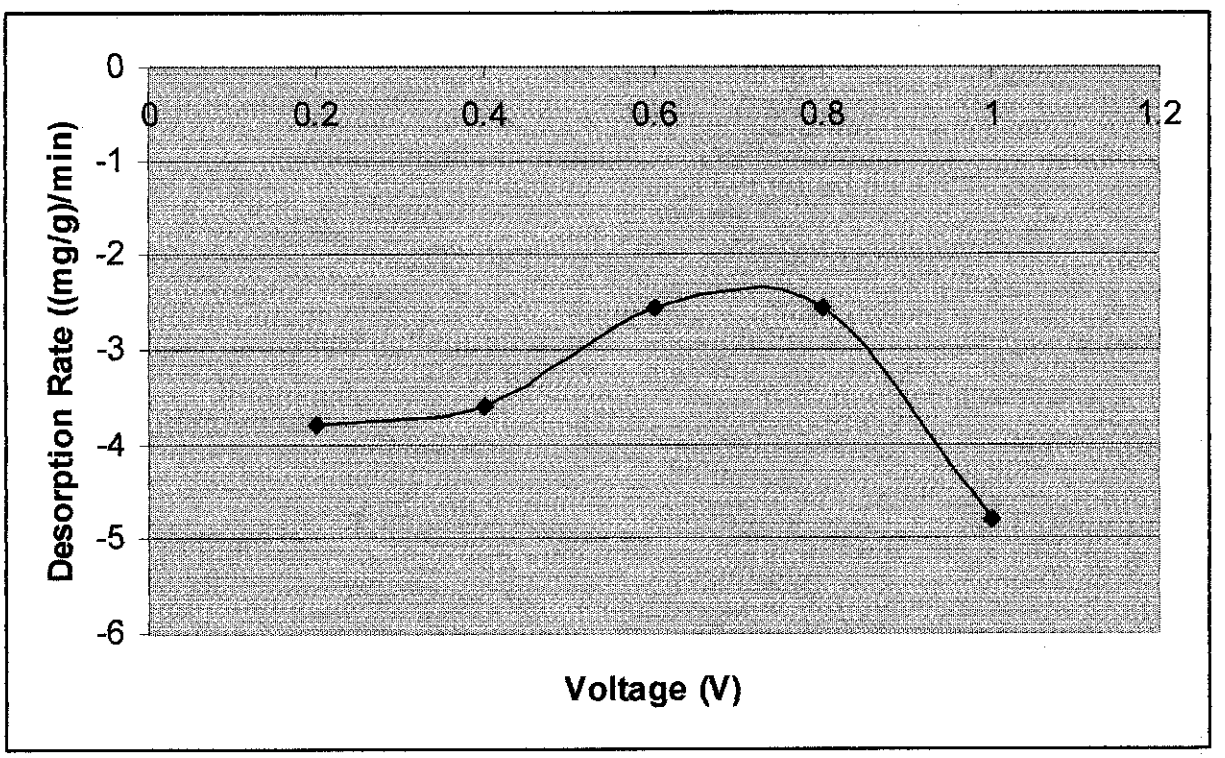


Figure 4.15: The Rate of Desorption vs. Voltage

Fig. 4.15 showed the effect of increasing voltage towards the rate of desorption. The results also showed inconsistency of the desorption rate with respect to the applied voltage. However, considering the voltage application at 0.6, 0.8 and 1.0 V, the rate of desorption increased with increasing voltage. This result is to be expected because by applying more heat through electrical energy, the amount of energy absorbed by the GAC increased. Since the heat of adsorption is only about 30 kJ mol^{-1}, therefore the additional electrical energy which is converted through Ohmic heating supports the desorption mechanism where desorption process is accompanied by an increasing energy within the GAC.

4.3.5 Hysterisis Effect on Adsorption and Desorption Process of GAC

These figures below from Fig. 4.16 to 4.20 are to show the effectiveness of the regeneration process through Electrical Enchanced Adsorption (ESA) technique. Hysteris is a property of the GAC where the adsorption uptake value is not the same with desorption reduction value.

The hysterisis phenomena results shown below are expected for adsorption and desorption process. This is because during the adsorption process, the rapid climb in the amount of CO_2 uptake is because the GAC condition started with a very low CO^2 adsorbate inside, therefore as adsorption started the CO_2 quickly diffuse into the GAC pores. It become stable when the GAC pores is almost saturated with CO_2.

During desorption process, the rapid reduction of CO_2 uptake occurred because the purge gas rapidly remove the CO_2 saturated GAC. After a time, the reduction become slower because all of the CO_2 adsorbate has been removed except for the adsorbate that have undergo solid diffusion during adsorption process.

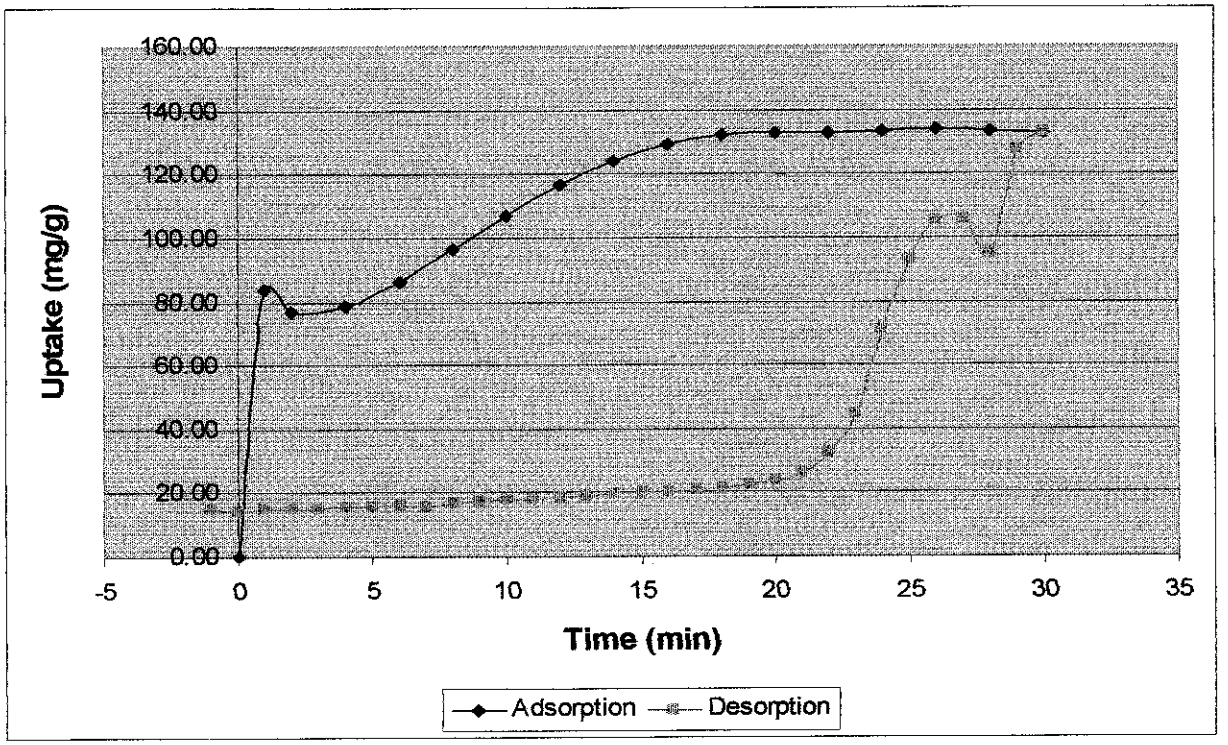


Figure 4.16: Exp 1, Hysterisis Effect on Adsorption (2V) and Desorption (1.0V) P

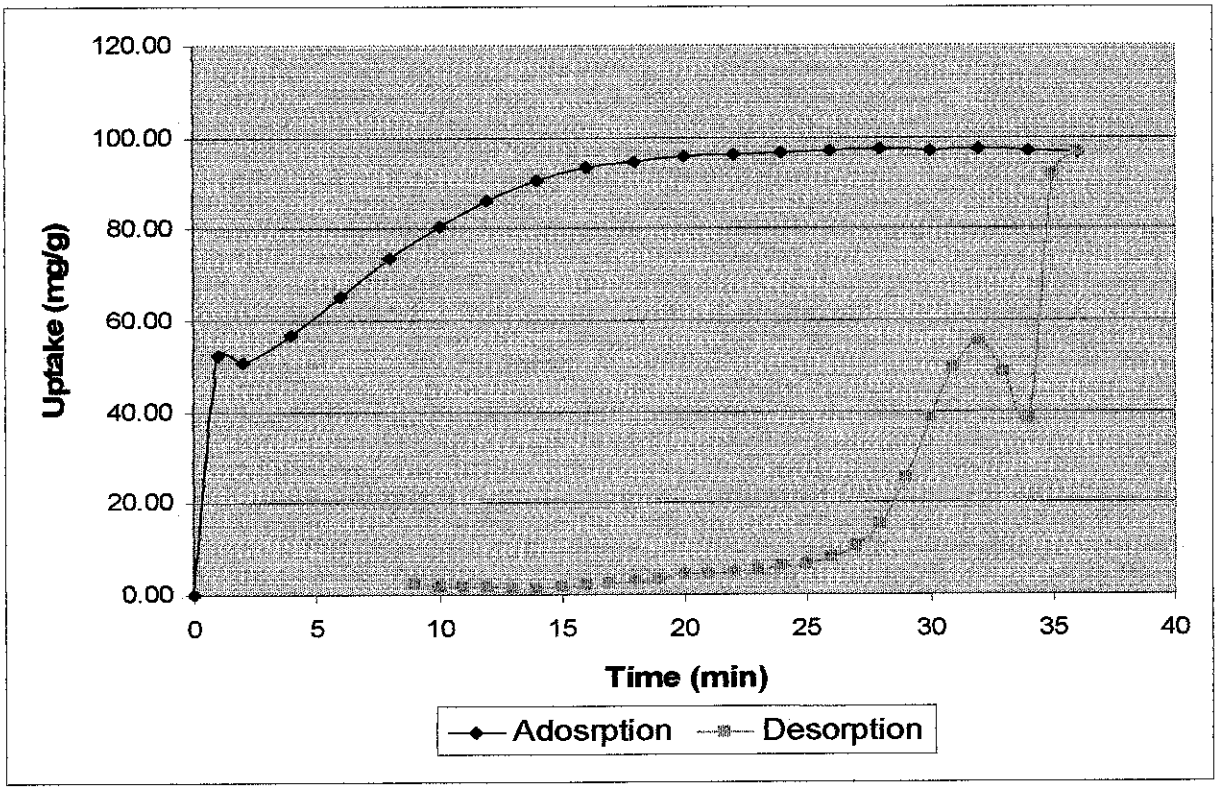


Figure 4.17: Exp 2, Hysterisis Effect on Adsorption (4V) and Desorption (0.2V)

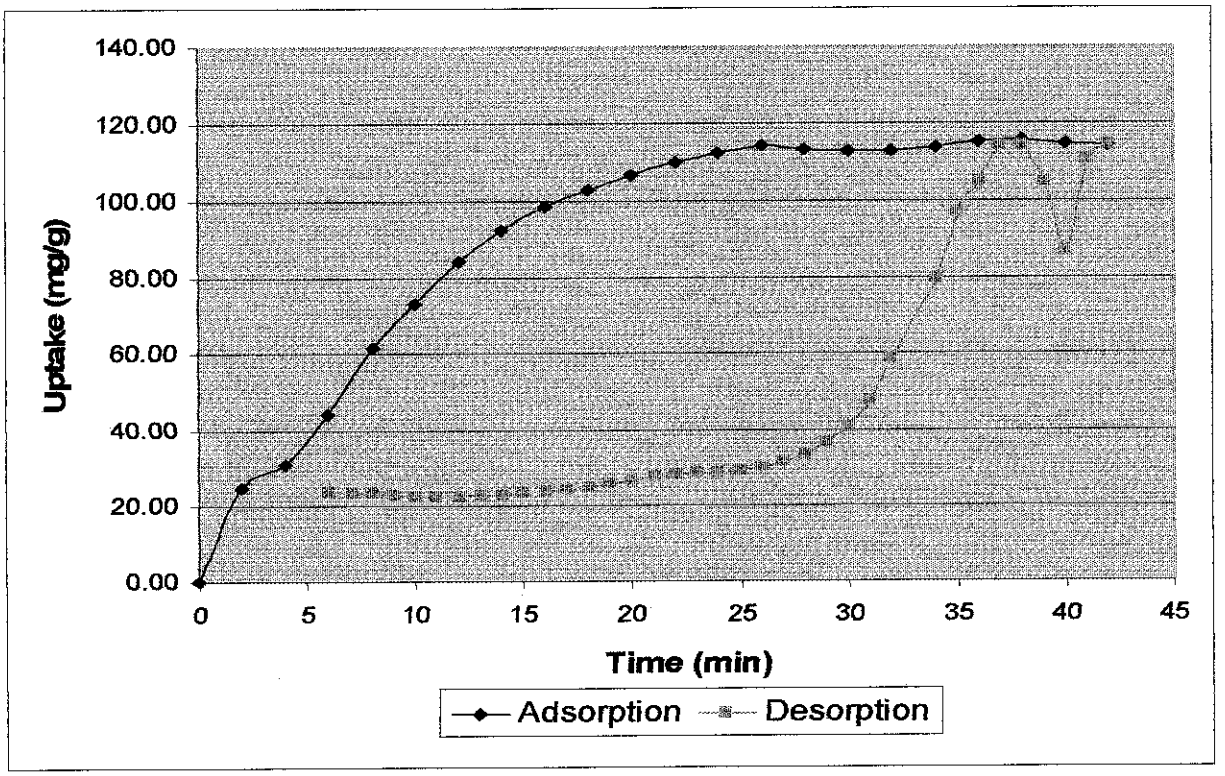


Figure 4.18: Exp 2, Hysterisis Effect on Adsorption (6V) and Desorption (0.4V)

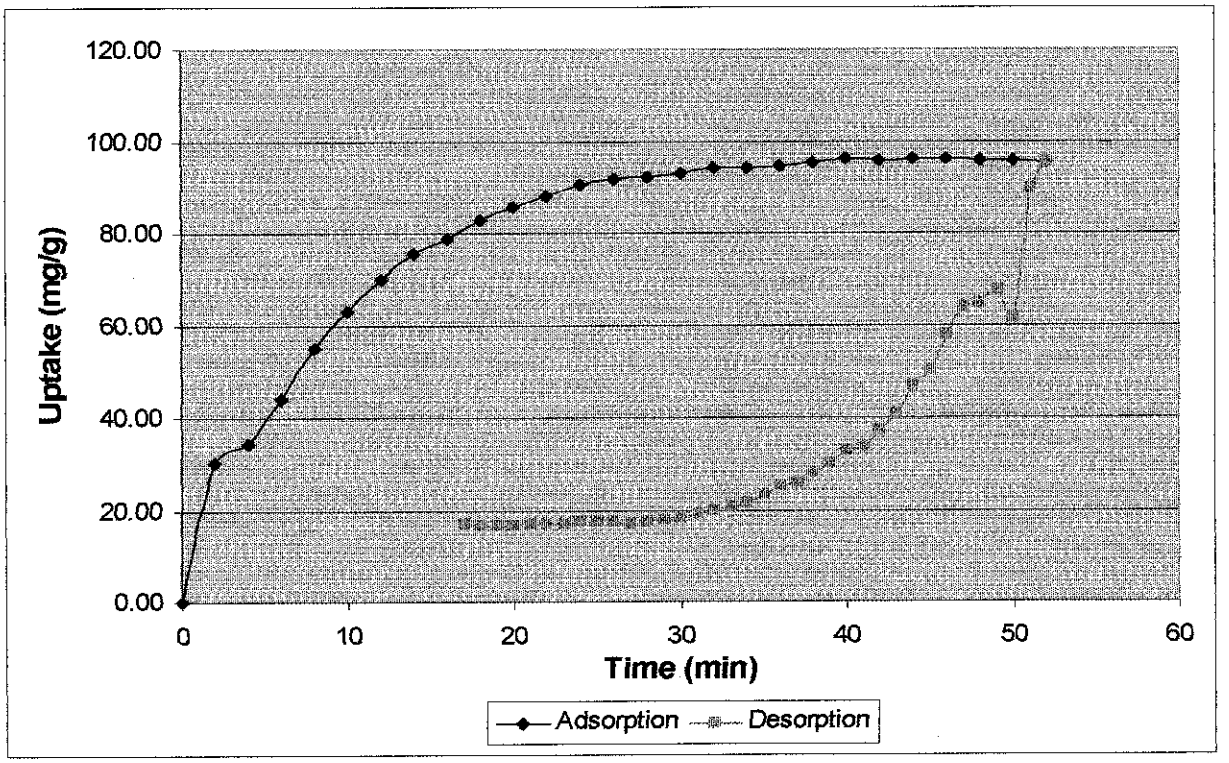


Figure 4.19: Exp 2, Hysterisis Effect on Adsorption (8V) and Desorption (0.6V)

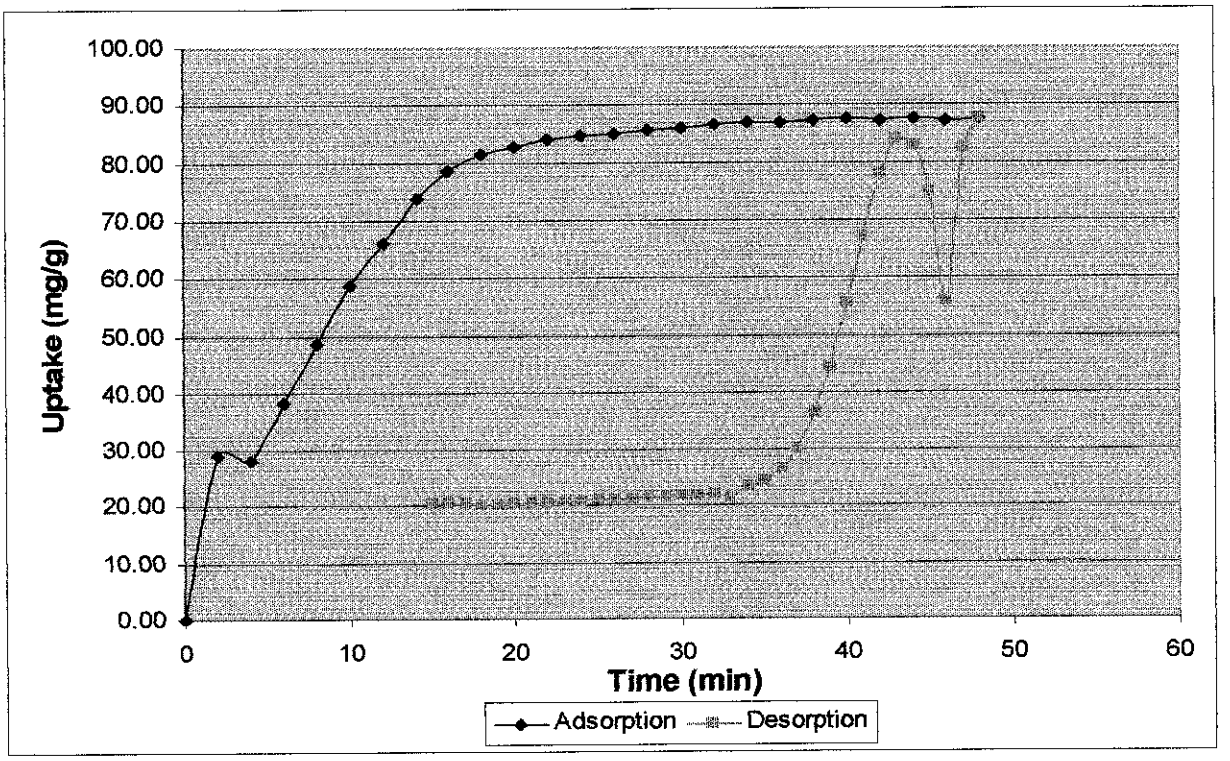


Figure 4.20: Exp 2, Hysterisis Effect on Adsorption (10V) and Desorption (0.8V)

4.3.6 The Changes of Temperature Profile During Adsorption Process

During the adsorption process, a similar trend of temperature changes is observed with respect to the amount of CO_2 uptake.

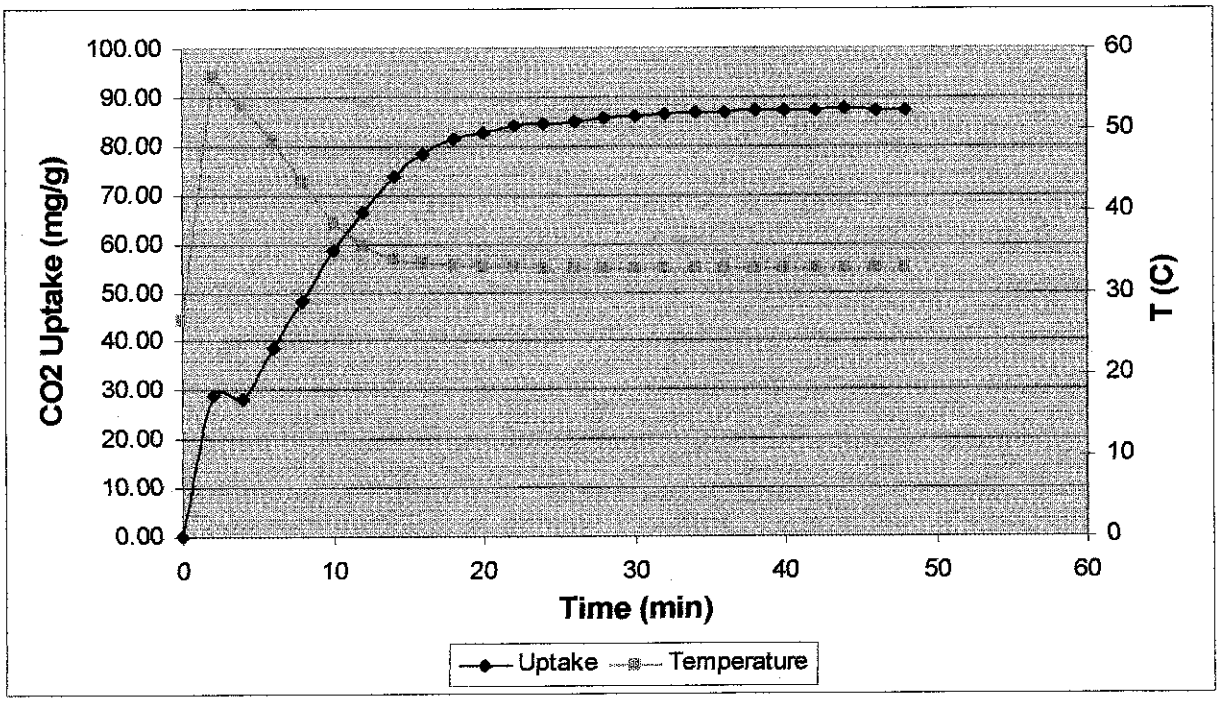


Figure 4.21: The Response of Temperature on the Adsorption (2V) vs Time

Fig. 4.21 shows the trend of the temperature changes during the adsorption process at application of 2 V. Other graphical results of the increasing voltage application can be referred to Appendix in the APPENDIX section.

The temperature increased rapidly immediately after the experiment started. The rapid increase of temperature is due to the heat of adsorption during the adsorption process. As explained previously, during adsorption there is a reduction of energy the GAC. Since adsorption is an exothermic process, these heat is released towards the surrounding, which is the environment within the column and rising the temperature inside the column.

The phenomena can be associated with the knowledge that a rapid adsorption occurred during the initial state of the experiment. Therefore, an enormous amount of energy is released and increases the temperature up to 56.8 °C. Then the temperature slowly decreases despite the exothermic effect of adsorption. This occurred due to the

CO_2 adsorbate has a lower temperature, and the excess CO_2 removed the heat from the column. The equilibrium temperature for all the experiment didn't show specific temperature point but settled down within the range of 20 – 30 °C.

4.3.7 The Changes of Temperature Profile During Desorption Process

A similar trend of temperature changes was also observed during the desorption process for every experiment conducted at different voltage.

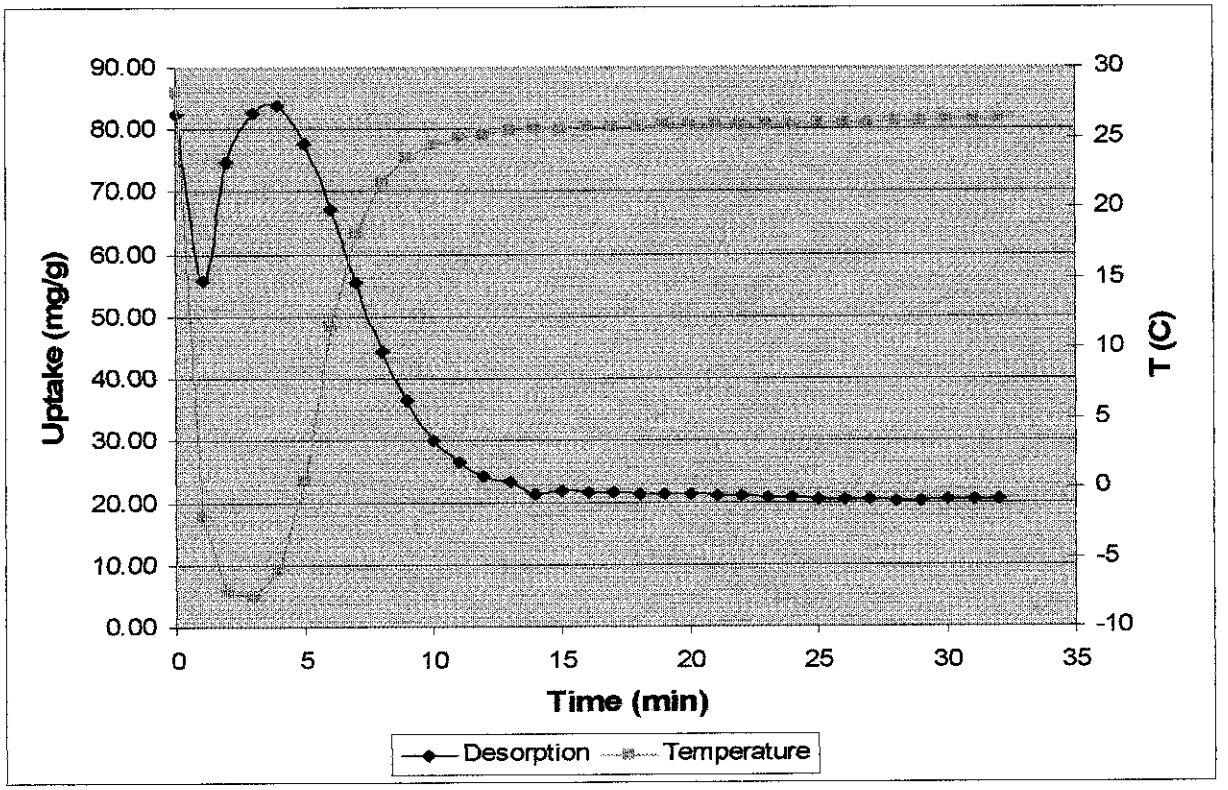


Figure 4.22: The Response of Temperature on the Desorption (1V) vs Time

Since desorption process, is an endothermic process, the GAC absorb heat from the heat supplied electrically. As shown in Fig. 4.22, the temperature decreases significantly during the initial of the experiment. During initial desorption process, the rate of CO_2 uptake reduction is very high. This causes a large endothermic process occurring within the column. The temperature fall up until -16.2 °C because the surrounding heat is absorbed by the GAC, therefore reduce the surrounding temperature. Then, the temperature slowly increased until reaching equilibrium temperature near the room temperature. The equilibrium temperatures for all the experiments are near the room temperature within 23-27 °C.

4.4 Errors in the experiment

During the experiment, various might have occurred that may have been affecting the precision and the accuracy of the data obtained from the conducted experiment. These errors are explained as below:

a) **Weight Measurement**

The experiment is conducted using a Mettle Toledo Balance. This equipment provides a quite precise value to about 3 decimal points. However, due to its high sensitivity, any vibration or undesired movement on or near the balance may have affect to the fluctuation of the weight observed. Here are the possible sources of vibration:

i) The DC generator place on the bench near the weight balance may have because vibration due to the motors used.

ii) The connection of tubing and electrical connection to the vessel have caused source of movement affecting the balance. Movement may have been from the wire pulling each other creating a small movement, invisible to the eye. Also, since the experiment was conducted at a range of temperature, the thermal expansion of the electrical wire can also cause the motion affecting the balance.

b) **Leakage**

The connection of the tubing is prepared manually using PVC and Teflon tape to sealed possible source of leakage. Despite having a "free leakage" through the leakage test, there might still some possibilities of leakage:

i) Tubing T-junction connection

ii) The tubing and gas cylinder connection

iii) Through the gap between the tubing and the copper wire.

iv) Between one type of tubing and another.

v) Through the hole having the digital thermometer probe into the vessel

c) **Gas Flow**

During the experimental work, the gas flow was supposed to be maintained at 20 kPa. However there was a fluctuation of ± 3 kPa from the desired value. The fluctuation will of course affect the adsorption and desorption rate since physical adsorption depends on the effect of pressure. The gas regulator used for the experiment may have been the cause of fluctuation.

d) **Human Error**

Human error is unavoidable but is minimally done during the experimental work. Possible areas affected by human errors are:

i) Manually reading and the adjustment of the Voltmeter and Ammeter.

ii) The time sequence for taking a reading of the Pressure, Temperature and Weight

iii) The preparation gap between the changing from adsorbs gas CO_2 to the purging gas N_2 or He.

e) **Preparation of Activated Carbon**

The preparation of Activated Carbon is vital during the experiment. This is because the accuracy on how much the CO_2 uptake depends much on the prepared activated carbon.

i) The 20 minutes time allocated for regeneration, which is done purposely each time during the start of the experiment, may have not been adequate to have a highly regenerated activated carbon.

ii) Some of the data obtained is gotten from a repeated usage of the same activated carbon. Therefore the activity of the adsorbent may have been reduced after several usages.

iii) The activated carbon must be made sure to be dry before starting the experiment.

CHAPTER 5

CONLUSION AND RECOMMENDATIONS

5.1 Conclusion

The recently done study for the Electrical Swing Adsorption is quite similar to the previously done study. However, since the incremental of voltage in the previous study is not consistent, therefore the recent study focuses on having a consistent interval of voltage application. The reason is to obtain a better comparison with every consistent incremental of voltage.

During the experimental work, the Granular Activated Carbon is filled into the cylinder column. Since activated carbon has a good electrical conductivity, electrical current is applied onto it during the adsorption and desorption process. Based on the Ohmic Law, electrical energy is converted into heat that is used to supply energy towards GAC during adsorption and desorption process. The experiment is conducted using only 1.5 mm GAC due to limited time constraints adsorption voltage ranging from 2 – 10 V and desorption voltage from 0.2 – 1.0 V. Based on the analysis done, as the voltage is increased, the amount of CO_2 uptake reduced during adsorption and the amount of CO_2 reduction increased during desorption process. Voltage increment also reduced the rate of adsorption and increased the rate of desorption. It can be concluded that, adsorption is better done at lower voltage to increase the amount of uptake, while desorption is better done at a higher voltage for efficient regeneration of the GAC.

However, due to some equipment problems, there is also some inconsistency in the results obtained. Therefore for further studies, some improvement is suggested in order to gain precise and accurate data.

5.2 Recommendations

Although the experiment is being conducted for the 3rd time, further improvement needed to be done in order to improve the experimental setup to be reliable to be able to provide an accurate and firm data from for the research studies. Here are some suggestions to achieve the desired improvement:

5.2.1 Triplicate Results

Although mentioned in the previous report as part of the suggested improvement, the recent experiment conducted was also limited due to the time constraint. If time was not limited, the average data from triplicate results would be the best and precise data for the project. This way, it avoids inconsistency and reduces the margin of error.

5.2.2 Electrical Connection

In order to obtain the best conductor to supply the electrical energy, users are advised use a copper type wire since it provides excellent conductivity. An important thing is to make sure that the wire are insulated and the connection and is connected to the power supply using the crocodile clip instead of a bare wire. This is to ensure the safety of the user while handling with electrical current. This well seriously helps a lot to protect user from electrical shock since the voltage applied is quite harmful.

5.2.3 Type of Adsorbent

User should vary the type of GAC used by varying the size or their structure, granular or powdered and then compared which gives the superior advantage to the adsorption and selectivity.

Since the ESA technique is developed concurrently with the Carbon Fiber Composite Molecular Sieve – a type of adsorbent that is more superior in terms of uptake, structure and conductivity compared to granular activated carbon (GAC), the CFCMS adsorbent must be obtained to study the effectiveness of the adsorbent to the

adsorption of CO_2 using the ESA. User can also use several types of other adsorbent and conduct a research to determine which adsorbent give the highest selectivity and Uptake for CO_2.

5.2.4 Equipment Setup

The bench scale equipment still has a lot of room for improvement. Among the improvement needed are:

- Temperature Distribution – Previously using a digital thermometer (DT) which measures the temperature only a one point. Additional DT is required to observe the temperature change along the adsorption column.
- Flowmeter – Flowmeter equipment such as a rotameter, orifice or vortex flowmeter should be used to measure the flow rate instead of measuring using the pressure drop.
- Weight Measurement – A fixed type of weight measuring balance with a fixed electrical connection into the adsorption vessel should be used. This is to avoid the fluctuation of the measurement during the experiment.

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APPENDICES

APPENDIX 1: TABULATED DATA

APPENDIX 2: 1.5 MM GAC TEMPERATURE PROFILE DATA TOWARDS ADSORPTION AND DESORPTION

APPENDIX 3: SCHEMATIC DIAGRAM FOR OF THE ESA EXPERIMENTAL SETUP FOR ADSORPTION / DESORPTION PROCESS

APPENDIX 1:

TABULATED RAW DATA FROM EXPERIMENT CONDUCTED

Exp 1: Adsorption at 2V, GAC Weight = 79.88g, Purging gas = He						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	0	23.6	0	0	0.00	0
1	6.67	56.8	21	2	83.50	19
2	6.13	54.6	21	2	76.74	19
4	6.29	49.9	22	2	78.74	20
6	6.88	44	21	2	86.13	19
8	7.7	35.9	20	2	96.39	18
10	8.53	29.4	21	2	106.79	19
12	9.3	26.1	20	2	116.42	18
14	9.93	24.7	21	2	124.31	19
16	10.32	24	21	2	129.19	19
18	10.56	23.8	21	2	132.20	19
20	10.6	23.6	20	2	132.70	18
22	10.62	23.5	20	2	132.95	18
24	10.65	23.3	20	2	133.32	18
26	10.7	23.1	20	2	133.95	18
28	10.64	23	20	2	133.20	18
30	10.63	23	20	2	133.07	18

Exp 1: Desorption at 1.0V, GAC Weight = 79.88g, Purging Gas = He						
Time	Weight	Temp	P1	P2	Uptke (mg/g)	ΔP (P1 – P2)
0	10.21	21	0	0	127.82	0
1	7.58	-16.2	19	2	94.89	17
2	8.44	-16.2	19	2	105.66	17
3	8.4	-10.1	19	2	105.16	17
4	7.44	9.4	20	2	93.14	18
5	5.67	18.5	20	2	70.98	18
6	3.56	21.4	20	2	44.57	18
7	2.57	22.3	20	2	32.17	18
8	2.08	22.7	20	2	26.04	18
9	1.9	22.9	20	2	23.79	18
10	1.78	23.1	20	2	22.28	18
11	1.72	23.2	20	2	21.53	18
12	1.68	23.3	20	2	21.03	18
13	1.63	23.4	20	2	20.41	18
14	1.6	23.5	20	2	20.03	18
15	1.58	23.5	20	2	19.78	18
16	1.53	23.5	20	2	19.15	18
17	1.49	23.6	20	2	18.65	18
18	1.43	23.6	20	2	17.90	18
19	1.42	23.6	20	2	17.78	18
20	1.39	23.6	20	2	17.40	18
21	1.33	23.6	20	2	16.65	18
22	1.25	23.6	20	2	15.65	18
23	1.27	23.6	20	2	15.90	18
24	1.26	23.7	20	2	15.77	18
25	1.23	23.7	20	2	15.40	18
26	1.22	23.7	20	2	15.27	18
27	1.21	23.7	20	2	15.15	18
28	1.2	23.7	20	2	15.02	18
29	1.15	23.8	21	2	14.40	19
30	1.19	23.7	21	2	14.90	19

Exp 2: Adsorption at 4.0V, GAC Weight = 80.4 g, Purging Gas = He						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	0	25	0	0	0.00	0
1	4.22	58	23	2	52.49	21
2	4.09	56	22	2	50.87	20
4	4.56	51.5	22	2	56.72	20
6	5.23	46.2	21	2	65.05	19
8	5.92	38.7	22	2	73.63	20
10	6.46	32.3	22	2	80.35	20
12	6.93	28.1	22	2	86.19	20
14	7.27	26.3	21	2	90.42	19
16	7.51	25.3	22	2	93.41	20
18	7.62	24.9	22	2	94.78	20
20	7.72	24.7	22	2	96.02	20
22	7.75	24.4	21	2	96.39	19
24	7.78	24.4	22	2	96.77	20
26	7.8	24.2	21	2	97.01	19
28	7.82	24.2	23	2	97.26	21
30	7.8	24	21	2	97.01	19
32	7.82	23.9	21	1	97.26	20
34	7.8	23.8	21	1	97.01	20
36	7.78	23.7	20	1	96.77	19

Exp 2: Desorption at 0.2V, GAC Weight = 80.4 g, Purging Gas = He						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	7.38	21.7	0	0	91.79	0
1	3.09	-14.2	18	1	38.43	17
2	3.9	-15.2	19	1	48.51	18
3	4.43	-12.2	20	2	55.10	18
4	3.97	1.5	20	1	49.38	19
5	3.11	15.6	20	1	38.68	19
6	2.05	20	20	1	25.50	19
7	1.24	21.9	20	1	15.42	19
8	0.85	22.5	20	1	10.57	19
9	0.64	22.9	20	1	7.96	19
10	0.52	23.1	20	1	6.47	19
11	0.48	23.3	20	1	5.97	19
12	0.42	23.4	20	1	5.22	19
13	0.39	23.5	20	1	4.85	19
14	0.34	23.5	19	1	4.23	18
15	0.34	23.6	20	1	4.23	19
16	0.25	23.7	20	1	3.11	19
17	0.22	23.7	19	1	2.74	18
18	0.18	23.8	19	1	2.24	18
19	0.15	23.8	19	1	1.87	18
20	0.13	23.8	19	1	1.62	18
21	0.1	23.8	19	1	1.24	18
22	0.09	23.9	19	1	1.12	18
23	0.12	23.9	19	1	1.49	18
24	0.12	23.9	19	1	1.49	18
25	0.14	23.9	19	1	1.74	18
26	0.18	23.8	19	1	2.24	18

Exp 3: Adsorption at 6.0V, GAC Weight = 78.76 g, Purging Gas = N_2						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	0	23.5	0	0	0.00	0
2	1.94	50.1	24	1	24.63	23
4	2.46	46.3	22	2	31.23	20
6	3.51	42	22	2	44.57	20
8	4.86	34.8	20	2	61.71	18
10	5.74	30.6	22	2	72.88	20
12	6.62	27.4	22	2	84.05	20
14	7.26	25.8	22	2	92.18	20
16	7.77	25	21	2	98.65	19
18	8.1	24.6	20	2	102.84	18
20	8.41	24.4	20	2	106.78	18
22	8.64	24.3	20	2	109.70	18
24	8.85	24.3	21	2	112.37	19
26	9.01	23.9	19	1	114.40	18
28	8.93	24.1	23	2	113.38	21
30	8.87	23.8	21	2	112.62	19
32	8.88	23.7	19	1	112.75	18
34	8.95	23.7	19	1	113.64	18
36	9.08	23.7	21	1	115.29	20
38	9.09	23.5	20	2	115.41	18
40	9.03	23.6	21	2	114.65	19
42	9.01	23.7	23	2	114.40	21

Exp 3: Desorption at 0.4 V, GAC Weight = 78.76 g, Purging Gas = N_2						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	8.68	23.5	0	0	110.21	0
1	6.8	-8.7	19	2	86.34	17
2	8.23	-11.9	19	2	104.49	17
3	8.99	-11.4	19	2	114.14	17
4	9	-8	19	2	114.27	17
5	8.26	-3.1	19	2	104.88	17
6	7.62	4.9	19	2	96.75	17
7	6.23	14.1	19	2	79.10	17
8	4.63	18.5	19	2	58.79	17
9	3.75	20.5	19	2	47.61	17
10	3.22	21.5	19	2	40.88	17
11	2.89	22.1	19	2	36.69	17
12	2.63	22.4	19	2	33.39	17
13	2.48	22.7	19	2	31.49	17
14	2.37	22.9	19	2	30.09	17
15	2.3	23.1	19	2	29.20	17
16	2.24	23.2	19	2	28.44	17
17	2.24	23.3	19	2	28.44	17
18	2.21	23.4	19	2	28.06	17
19	2.17	23.4	19	2	27.55	17
20	2.11	23.5	19	2	26.79	17
21	2.02	23.6	19	2	25.65	17
22	1.96	23.6	19	2	24.89	17
23	1.92	23.7	19	2	24.38	17
24	1.89	23.7	19	2	24.00	17
25	1.86	23.7	19	2	23.62	17
26	1.8	23.8	19	2	22.85	17
27	1.8	23.8	19	2	22.85	17
28	1.77	23.8	20	2	22.47	18
29	1.76	23.8	20	2	22.35	18
30	1.77	23.8	20	2	22.47	18
31	1.81	23.8	20	2	22.98	18
32	1.84	23.8	20	2	23.36	18
33	1.84	23.8	20	2	23.36	18
34	1.88	23.9	20	2	23.87	18

Exp 4: Adsorption at 8 V, GAC Weight = 77.26 g, Purging Gas = N_2						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	0	23.4	0	0	0.00	0
2	2.34	46.2	23	2	30.29	21
4	2.65	42.3	20	1	34.30	19
6	3.4	39.2	20	1	44.01	19
8	4.26	36.5	24	2	55.14	22
10	4.88	33.7	20	1	63.16	19
12	5.4	31.8	22	2	69.89	20
14	5.83	30.3	24	2	75.46	22
16	6.1	28.7	20	1	78.95	19
18	6.4	27.6	22	2	82.84	20
20	6.63	26.8	22	2	85.81	20
22	6.79	26.2	22	1	87.89	21
24	7	25.8	23	2	90.60	21
26	7.09	25.4	23	2	91.77	21
28	7.13	25.2	22	1	92.29	21
30	7.19	25.1	22	2	93.06	20
32	7.26	25.1	24	2	93.97	22
34	7.27	24.9	21	1	94.10	20
36	7.3	24.9	23	2	94.49	21
38	7.37	24.8	22	2	95.39	20
40	7.42	25	25	2	96.04	23
42	7.4	24.8	21	2	95.78	19
44	7.42	25	24	2	96.04	22
46	7.43	24.8	21	2	96.17	19
48	7.39	24.8	21	1	95.65	20
50	7.4	24.8	21	1	95.78	20
52	7.37	24.9	22	2	95.39	20

Exp 4: Desorption at 0.6 V, GAC Weight = 77.26 g, Purging Gas = N_2						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	6.93	22.3	0	0	89.70	0
1	4.76	1.5	18	1	61.61	17
2	5.2	-1.3	20	1	67.31	19
3	5.01	0	20	1	64.85	19
4	4.94	2.3	20	1	63.94	19
5	4.46	4.1	20	1	57.73	19
6	3.87	6.4	20	1	50.09	19
7	3.62	8.3	20	1	46.85	19
8	3.16	10.5	20	1	40.90	19
9	2.88	12	20	1	37.28	19
10	2.6	13.7	20	1	33.65	19
11	2.54	15.2	20	1	32.88	19
12	2.31	16.4	20	1	29.90	19
13	2.16	17.8	20	1	27.96	19
14	2	19.1	20	1	25.89	19
15	1.94	20.1	20	1	25.11	19
16	1.79	20.8	20	1	23.17	19
17	1.65	21.3	20	1	21.36	19
18	1.59	21.7	21	1	20.58	20
19	1.53	22	21	1	19.80	20
20	1.47	22.2	21	1	19.03	20
21	1.42	22.4	21	1	18.38	20
22	1.37	22.5	21	1	17.73	20
23	1.34	22.7	21	1	17.34	20
24	1.32	22.7	21	1	17.09	20
25	1.35	22.9	21	1	17.47	20
26	1.34	22.9	21	2	17.34	19
27	1.33	23	21	2	17.21	19
28	1.32	23.1	21	2	17.09	19
29	1.31	23.2	21	2	16.96	19
30	1.3	23.2	21	2	16.83	19
31	1.29	23.2	21	2	16.70	19
32	1.27	23.2	21	2	16.44	19
33	1.29	23.3	21	2	16.70	19
34	1.3	23.3	21	2	16.83	19

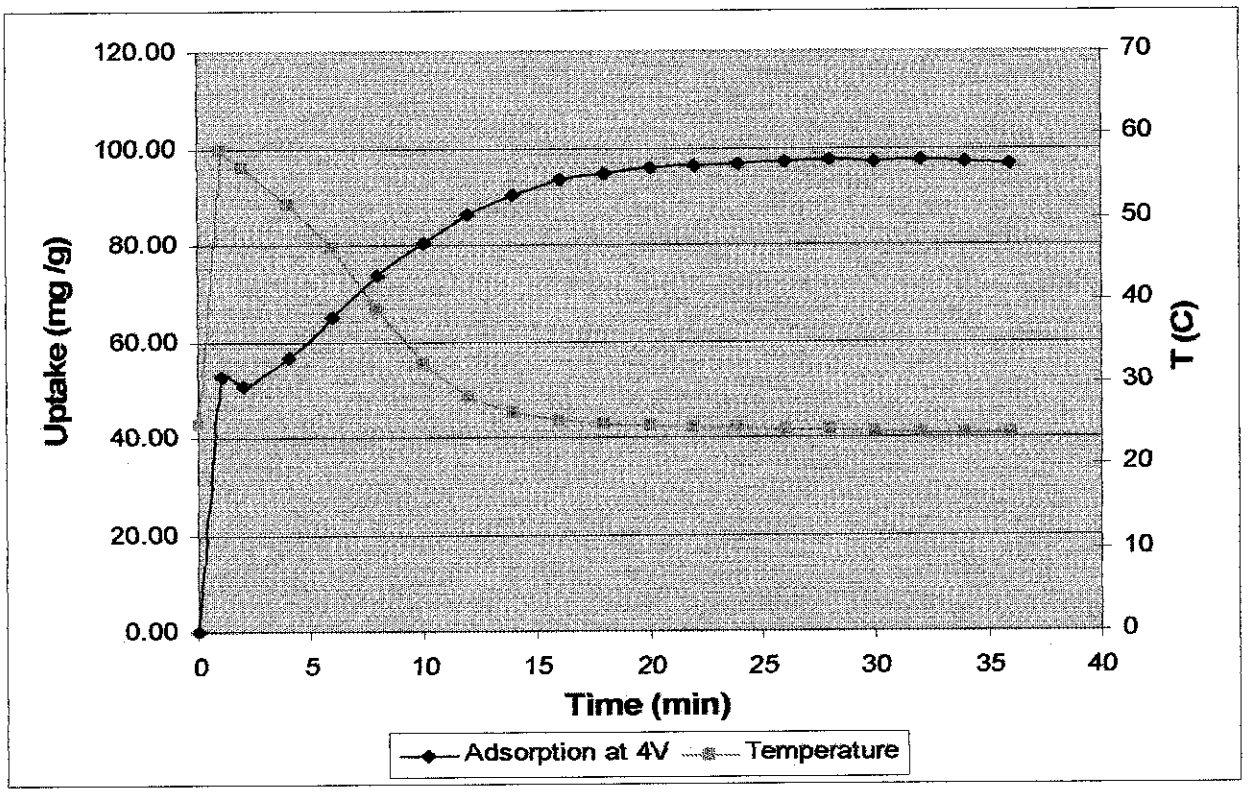
Exp 5: Adsorption at 10 V, GAC Weight = 79.27 g, Purging Gas = N_2						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	0	26.7	0	0	0.00	0
2	2.31	56.6	22	2	29.14	20
4	2.24	52.8	21	2	28.26	19
6	3.05	48.6	23	2	38.48	21
8	3.84	43.5	22	2	48.44	20
10	4.65	38.5	23	2	58.66	21
12	5.25	35.6	21	2	66.23	19
14	5.85	34	21	2	73.80	19
16	6.22	33.5	21	2	78.47	19
18	6.46	33.3	21	2	81.49	19
20	6.56	33.2	21	2	82.76	19
22	6.67	33.1	21	2	84.14	19
24	6.71	33	21	2	84.65	19
26	6.74	32.9	21	2	85.03	19
28	6.78	32.9	20	2	85.53	18
30	6.81	32.9	20	2	85.91	18
32	6.86	32.8	20	2	86.54	18
34	6.88	32.8	20	2	86.79	18
36	6.89	32.8	20	1	86.92	19
38	6.91	32.8	20	1	87.17	19
40	6.93	32.9	20	1	87.42	19
42	6.92	32.9	20	1	87.30	19
44	6.95	33	20	1	87.68	19
46	6.92	33	20	1	87.30	19
48	6.93	33	20	1	87.42	19

Exp 5: Desorption at 0.8 V, GAC Weight = 79.27 g, Purging Gas = N_2						
Time	Weight	Temp	P1	P2	Uptake (mg/g)	ΔP (P1 – P2)
0	6.54	28.2	0	0	82.50	0
1	4.43	-2.2	21	2	55.88	19
2	5.92	-7.5	20	2	74.68	18
3	6.56	-7.8	19	2	82.76	17
4	6.65	-6	20	2	83.89	18
5	6.17	0.4	20	2	77.84	18
6	5.32	11.6	19	1	67.11	18
7	4.4	18	19	1	55.51	18
8	3.51	21.8	19	1	44.28	18
9	2.89	23.5	21	1	36.46	20
10	2.39	24.4	19	1	30.15	18
11	2.1	24.9	19	1	26.49	18
12	1.92	25.2	18	1	24.22	17
13	1.85	25.4	20	2	23.34	18
14	1.7	25.6	20	2	21.45	18
15	1.74	25.6	19	1	21.95	18
16	1.72	25.7	18	1	21.70	17
17	1.71	25.7	20	2	21.57	18
18	1.69	25.7	19	1	21.32	18
19	1.69	25.8	20	2	21.32	18
20	1.68	25.8	19	1	21.19	18
21	1.67	25.8	18	1	21.07	17
22	1.66	25.9	20	2	20.94	18
23	1.64	25.9	20	2	20.69	18
24	1.64	25.9	19	1	20.69	18
25	1.63	26	18	1	20.56	17
26	1.62	26	20	2	20.44	18
27	1.61	26	19	2	20.31	17
28	1.6	26.1	20	2	20.18	18
29	1.6	26.1	20	2	20.18	18
30	1.61	26.2	19	1	20.31	18
31	1.62	26.2	19	1	20.44	18
32	1.61	26.2	20	2	20.31	18

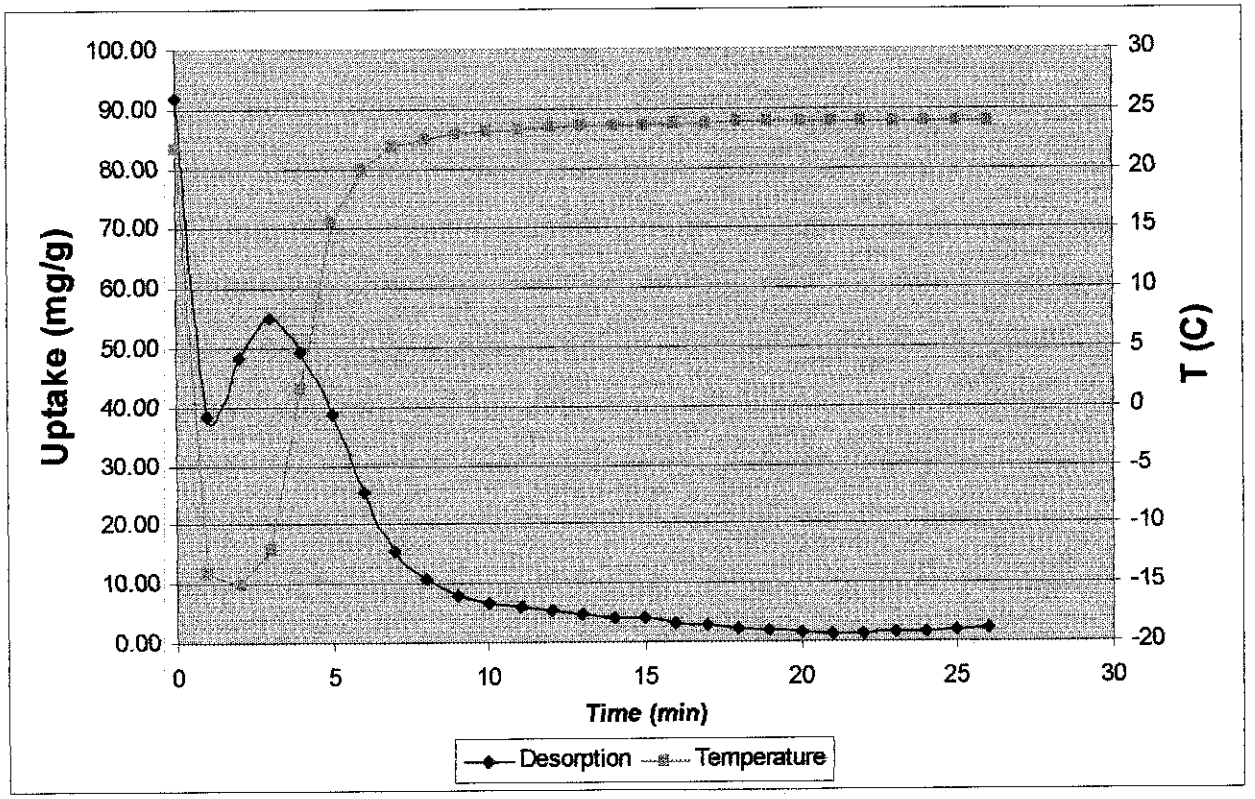
APPENDIX 2:

1.5 MM GAC TEMPERATURE PROFILE DATA TOWARDSADSORPTION AND DESORPTION

Experiment 2:

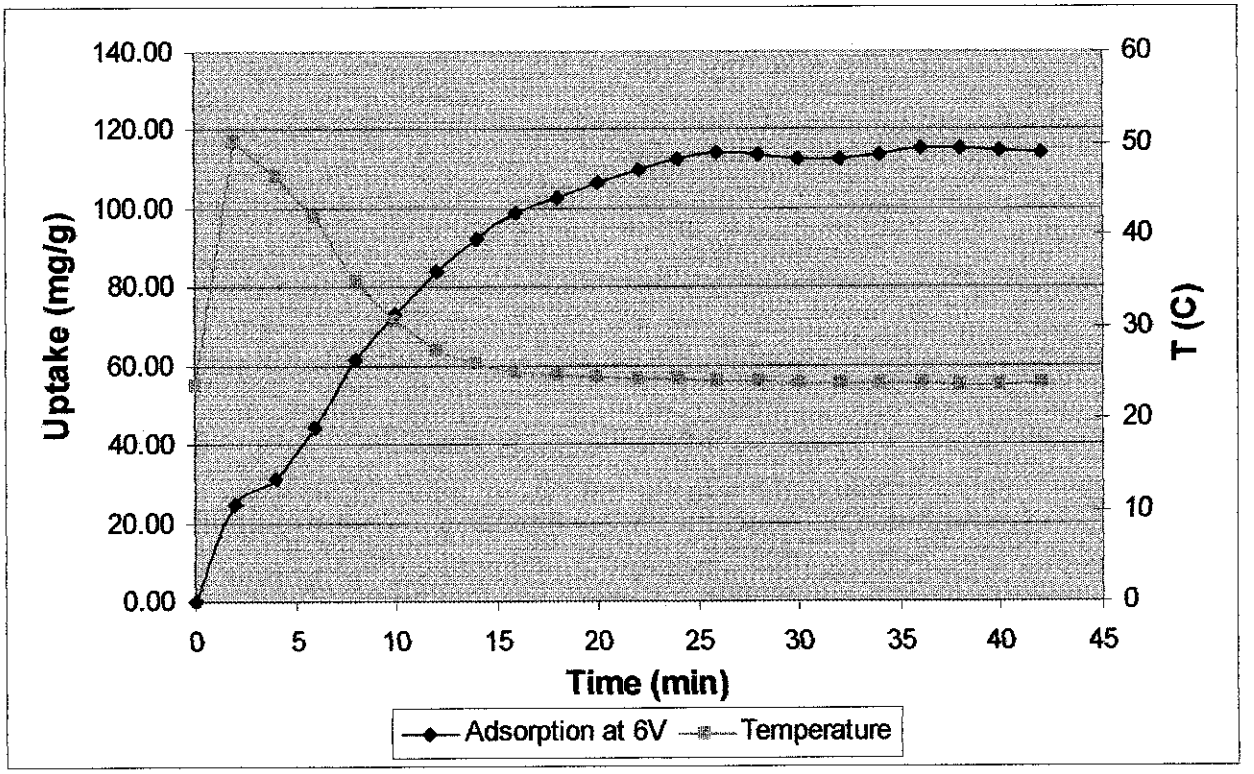


The Response of Temperature on the Adsorption (4 V) vs Time

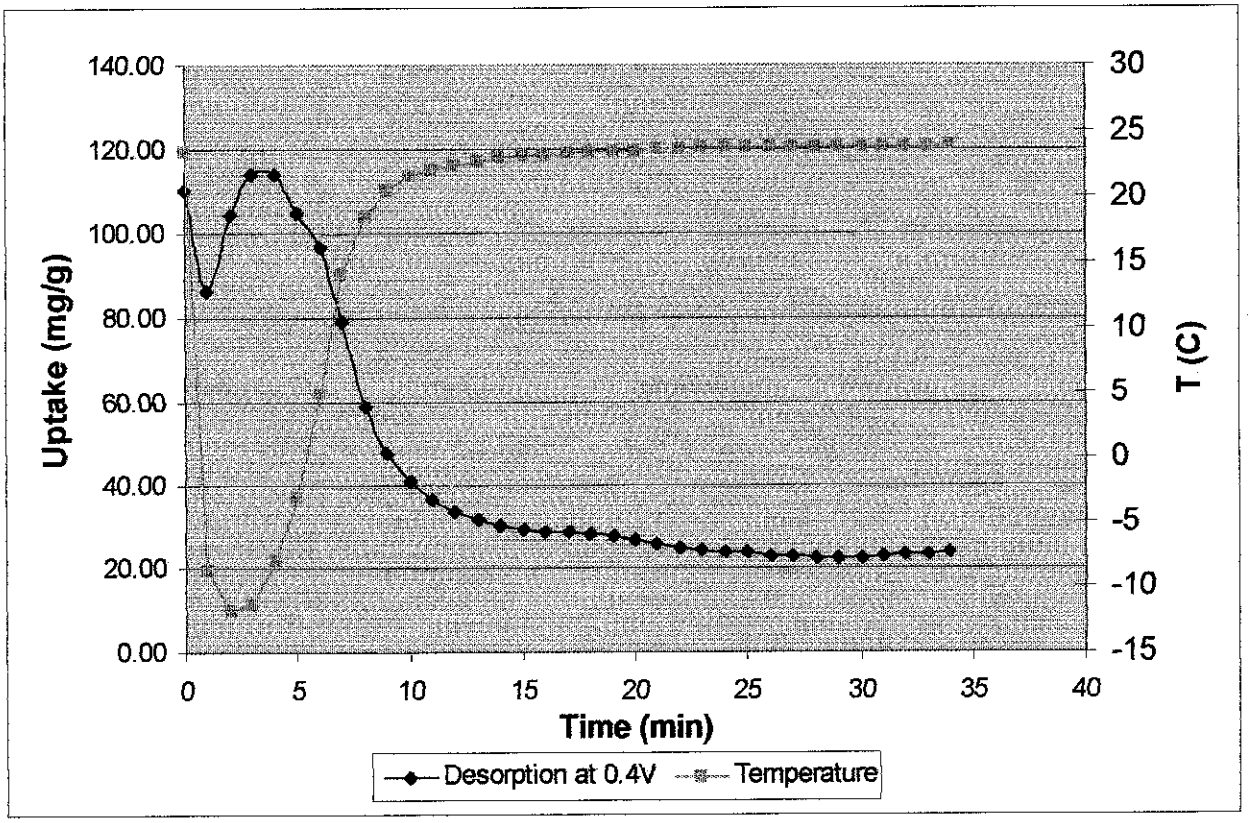


The Response of Temperature on the Desorption (0.2V) vs Time

Experiment 3:

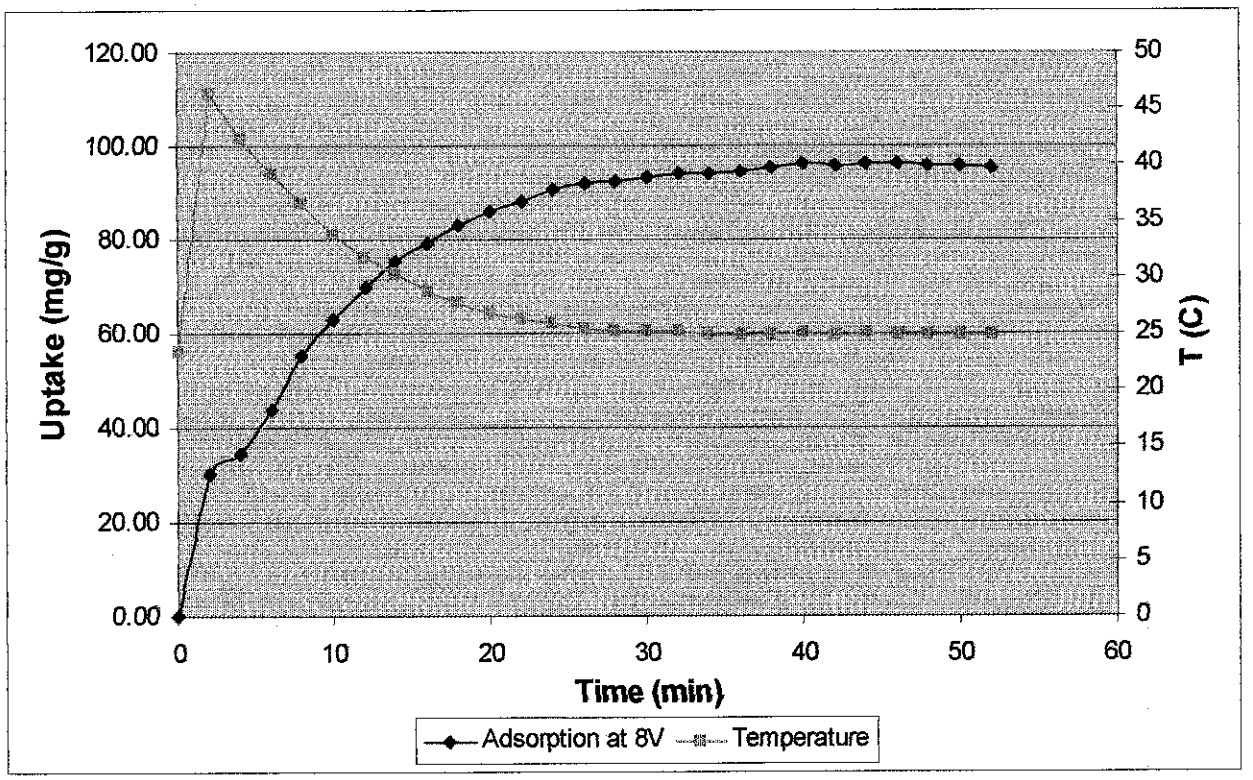


The Response of Temperature on the Adsorption (6 V) vs Time

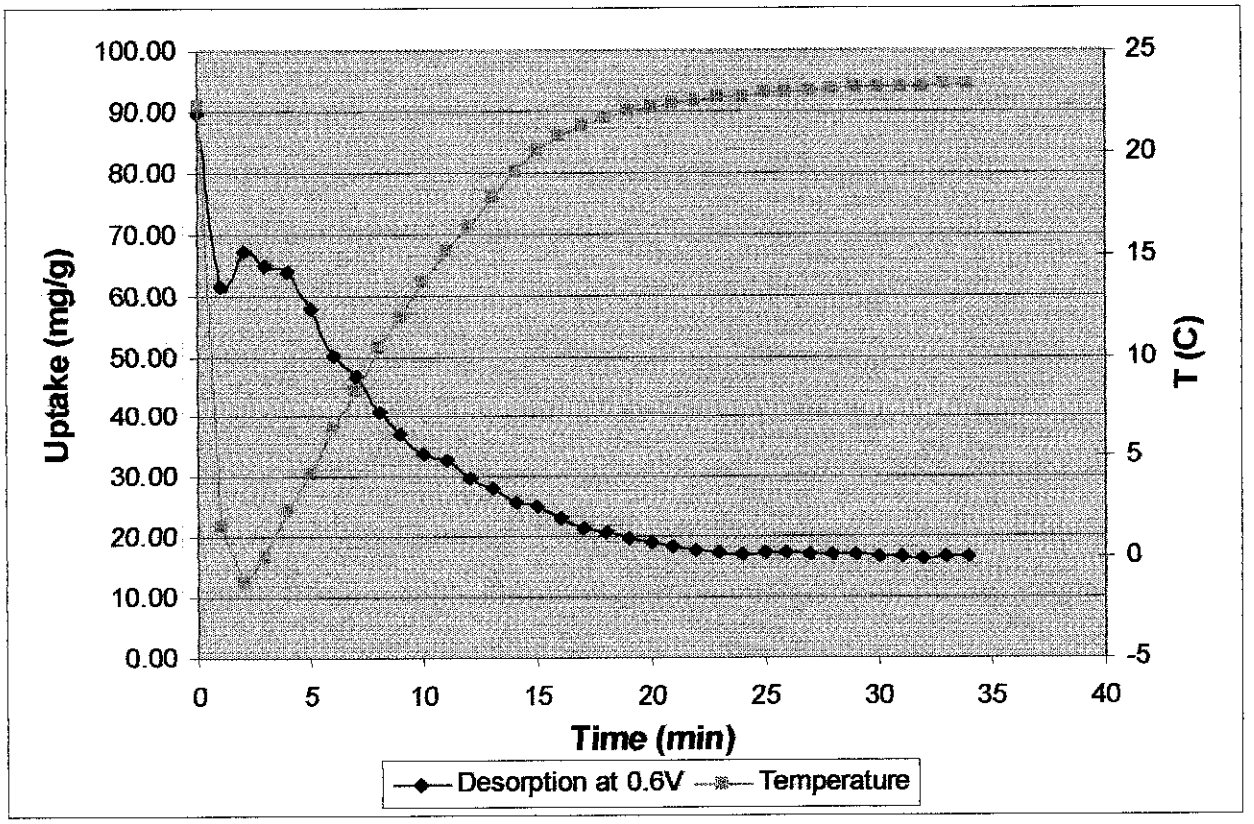


The Response of Temperature on the Desorption (0.4 V) vs Time

Experiment 4:

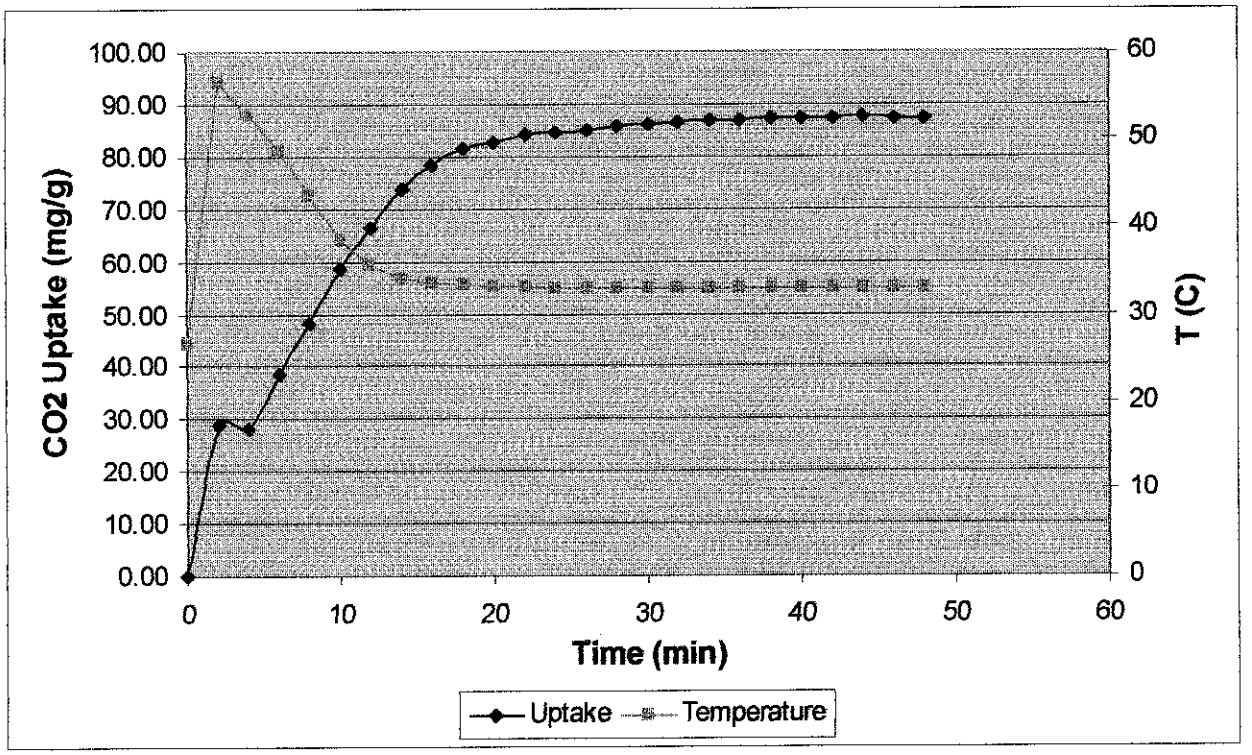


The Response of Temperature on the Adsorption (8 V) vs Time

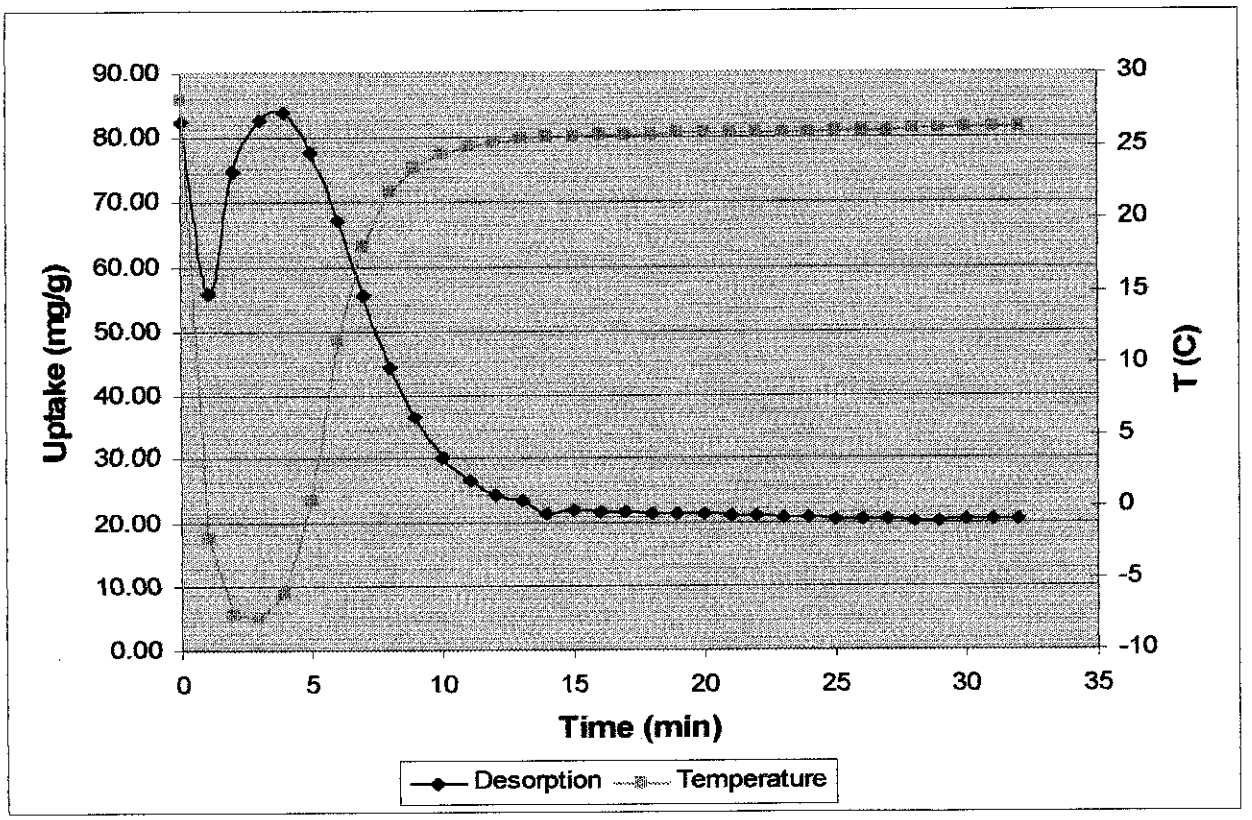


The Response of Temperature on the Desorption (0.6 V) vs Time

Experiment 5:



The Response of Temperature on the Adsorption (10 V) vs Time



The Response of Temperature on the Desorption (0.8 V) vs Time

APPENDIX 3:

SCHEMATIC DIAGRAM FOR OF THE ESA EXPERIMENTAL SETUP FOR ADSORPTION / DESORPTION PROCESS